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Assessment of Options for Extending the Life of the Hubble Space Telescope

Final Report

Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope
Space Studies Board
Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by William H. Press, Los Alamos National Laboratory, and John Ahearne, Sigma Xi. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

BACKGROUND

The Hubble Space Telescope (HST) was launched from the space shuttle in 1990 and has operated continuously in orbit for the past 14 years. HST was designed to be serviced by astronauts, and a series of four shuttle servicing missions from 1993 to 2002 replaced nearly all the key components except the original telescope mirrors and support structure. Three of the four servicing missions added major new instrument observing capabilities. A fifth planned mission, designated SM-4 (Servicing Mission-4), was intended to replace aging spacecraft batteries, fine-guidance sensors, and gyroscopes and install two new science instruments on the telescope.

Following the loss of the space shuttle Columbia and its crew in February 2003, NASA suspended all shuttle flights until the cause of the accident could be determined and steps taken to reduce the risks of future shuttle flights. In mid-January 2004 NASA decided, on the basis of risk to the astronaut crew, not to pursue the HST SM-4 mission. This cancellation, together with the predicted resulting demise of Hubble in the 2007-2008 time frame, prompted strong objections from scientists and the public alike. NASA continued to investigate options other than a shuttle astronaut mission for extending Hubble's science life and is currently in the early stages of developing an unmanned mission that would attempt to service Hubble robotically. NASA also plans to de-orbit HST by approximately 2013 by means of a robotic spacecraft.

This report assesses the options for extending the life of HST. In keeping with its statement of task (Appendix A), the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope assessed the scientific value of continued HST operation, issues of safety in using the space shuttle for servicing HST with an astronaut crew, the feasibility of robotic servicing, the impacts of servicing options on HST's science capability, and risk/benefit relationships between those servicing options deemed acceptable.

Approximately every decade the U.S. astronomical research community develops a decadal strategy for the field. A premise of the most recently developed strategy[1] was that the HST SM-4 mission was an integral part of NASA's facility planning for the future of the field and that this servicing mission would occur as planned at the time necessary to prevent the demise of the telescope. The strategy's advisory recommendations reflect this assumption, and the committee, which was neither asked nor constituted to address any possible changes in priorities for astronomical research or research facilities, assumed that NASA would follow the decadal survey advisory recommendations. If NASA concludes that it cannot move forward with portions of the decadal survey strategy, then NASA will have to carry out an in-depth examination of priorities for the research field. The committee does not endorse such a re-examination. The committee notes, however, that if a re-examination should occur it would have to be conducted in a very timely and very expeditious fashion in order to ensure the continued operation and integrity of Hubble.

ANTICIPATED HUBBLE FAILURES

The Hubble systems with the greatest likelihood of failing and thus ending or significantly degrading Hubble science operations are the gyroscopes, the batteries, and the fine-guidance sensor (FGS) units. In addition, the HST avionics system is vulnerable to the aging of the facility.

[1] National Research Council, 2001, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C.

The telescope uses three gyroscopes to provide precision attitude control. There are currently four functional gyros on HST—three in operation plus one spare. It is likely that the HST system will be reduced to two operating gyros in the latter half of 2006. The HST engineering team is currently working on approaches to sustaining useful, though potentially degraded, astronomical operations with only two gyros, and NASA expects to have that capability by the time it becomes necessary. Eventually, without servicing, the telescope will be reduced to operation with a single gyro in mid to late 2007. The spacecraft can be held in a safe configuration with one or no operating gyros, but science operations will not be possible.

Battery failures are another likely cause of loss of science operations. HST now has six batteries, of which five are necessary for full operations. If battery levels fall too low, the temperature of the structural elements in the Optical Telescope Assembly will fall below permissible levels, causing permanent damage to the facility. Recovery of scientific operations from this state is not possible.

The FGS units (in combination with their electronics subsystems) are used for precision pointing of the observatory. Two operating FGS units are required to support the HST observing program, with a third to supply redundancy. Based on recent test and performance data, one of the three currently operating FGS units is projected to fail sometime between October 2007 and October 2009, and a second is expected to fail sometime between January 2010 and January 2012.

Based on its examination of data and numerous technical reports on Hubble component operations, as well as discussions held with Hubble project personnel, the committee developed the following findings predicated on an estimated SM-4 earliest launch date of July 2006 and a most likely robotic mission launch date of February 2010.

FINDING: The projected termination in mid to late 2007 of HST science operations due to gyroscope failure and the projected readiness in early 2010 to execute the planned NASA robotic mission result in a projected 29-month interruption of science operations. No interruption of science operations is projected for a realistically scheduled SM-4 shuttle mission.

FINDING: The planned NASA robotic mission is less capable than the previously planned SM-4 shuttle astronaut mission with respect to its responding to unexpected failures and its ability to perform proactive upgrades. Combined with the projected schedule for the two options, the mission risk[2] associated with achieving at least 3 years of successful post-servicing HST science operations is significantly higher for the robotic option, with the respective risk numbers at 3 years being approximately 30 percent for the SM-4 mission and 80 percent for the robotics mission.

BENEFITS OF SERVICING HUBBLE

Impact of Hubble

Over its lifetime, HST has been an enormous scientific success, having earned extraordinary scientific and public recognition for its contributions to all areas of astronomy. Hubble is the most powerful space astronomical facility ever built, and it provides wavelength coverage and capabilities that are unmatched by any other optical telescope currently operating or planned.

The four key advantages that Hubble provides over most other optical astronomical facilities are unprecedented angular resolution over a large field, spectral coverage from the visible and the near infrared to the far ultraviolet, access to an extremely dark sky, and highly stable images that enable precision photometry. Hubble's imaging fields of view are also considerable, permitting mapping of extended objects and significant regions of sky. In contrast, ground-based telescopes have a view that is

[2] Mission risk is the risk of failing to achieve the mission objectives.

blurred by the atmosphere,[3] and they are completely blind in the ultraviolet and large portions of the near infrared. Hubble can see sharply and clearly at all wavelengths from the far ultraviolet to the near infrared. Hubble images are 5 to 20 times sharper than those obtained with standard ground-based telescopes, in effect bringing the universe that much "closer." Image sharpness and the absence of light pollution in orbit help Hubble to see objects 10 times fainter than even the largest ground-based telescopes. Moreover, Hubble's images are extremely stable, in contrast to those obtained with ground telescopes, whose view is continually distorted by changing atmospheric clarity and turbulence.

Singly, each of these advantages would represent a significant advance for science. Combined, they have made Hubble the most powerful optical astronomical facility in history. Hubble is a general-purpose national observatory that enables unique contributions to and insights concerning most astronomical problems of greatest current interest. Among the most profound contributions of Hubble have been the following:

- Direct observation of the universe as it existed 12 billion years ago,
- Measurements that helped to establish the size and age of the universe,
- Discovery of massive black holes at the center of many galaxies,
- Key evidence that the expansion of the universe is accelerating, which can be explained only by the existence of a fundamentally new type of energy, and therefore new physics, and
- Observation of proto-solar systems in the process of formation.

In addition to its impact on science, Hubble discoveries and images have generated intense public interest. Examples of Hubble data and images that have fascinated the public (and scientists) include the big "black eye" left by comet Shoemaker-Levy's direct hit on Jupiter's atmosphere, which alerted the public to the dangers of asteroids impacting Earth; a panoply of jewel-like planetary nebulas that illustrate the ultimate death of our Sun; portraits of planets in the solar system, including auroras on Jupiter and Saturn; and such astronomical spectacles as the "pillars of dust" in the Eagle Nebula that appeared on nearly every front page in America and became iconic for Hubble itself. The Hubble Space Telescope has clearly been one of NASA's most noticed science projects, garnering sustained public attention over its entire lifetime.

Maintaining and Enhancing Hubble's Capabilities

The four previous servicing missions to Hubble have added new observing modes and increased existing capabilities, typically by factors of between 10 and 100, since the telescope first flew in 1990. As a result, Hubble now produces more data per unit time than it did originally. The total rate of calibrated data has grown by a factor of 33 since launch.[4] A further increase was expected with the installation of the two new science instruments, the Wide-field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS), each of which would provide a greater than 10-fold improvement in scientific efficiency and sensitivity compared with previous instruments. Both of these instruments are already built.

With the installation of WFC3 and COS, and the continued operation enabled by a fifth servicing mission, a broad range of new discoveries would be expected from Hubble. In fact, the committee concluded that Hubble's promise for future discoveries following a fifth servicing mission would be comparable to the telescope's promise when first launched. For example, an important new technique

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[3] Adaptive optics are not able to give such stable images at such short wavelengths over such a wide field of view.

[4] Steve Beckwith, Space Telescope Science Institute/NASA, "Future Science Expected from HST," presentation for the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope, dated June 22, 2004.

that Hubble would offer for finding planets could enable detection of as many as 1000 new planets in the Milky Way Galaxy in the years after servicing. In addition, a large number of new supernovas could be found for the study of dark energy, reducing uncertainties in its properties by a factor of two. A wealth of data would also be collected to explore the nature of stars in the Milky Way Galaxy and in neighboring galaxies. Hubble is just now beginning to image objects being found by sister NASA missions such as Chandra (an x-ray observatory), Galaxy Evolution Explorer (GALEX; an ultraviolet imager), and Spitzer (an infrared imager and spectrograph), which are currently in orbit. These satellites are relatively wide-field survey telescopes whose goal in part is to detect objects for Hubble follow-up observations. These detailed follow-ups take time because of Hubble's smaller field of view; a large fraction of the scientific benefit of these other satellites will be lost if Hubble's mission is cut short prematurely. And finally, a servicing mission is needed to allow an orderly completion of large, homogeneous data sets such as spectral libraries and imaging surveys of large areas of the Milky Way Galaxy that Hubble is now gathering. These data sets will be archived to serve astronomers for decades to come, given that there are no foreseeable plans to replace Hubble with a telescope of comparable size, wavelength coverage, and high resolution.

The key findings of the committee related to the benefits of future servicing of Hubble are as follows:

FINDING: The Hubble telescope is a uniquely powerful observing platform in terms of its high angular resolution, broad wavelength coverage from the ultraviolet to the near infrared, low sky background, stable images, exquisite precision in flux determination, and significant field of view.

FINDING: Astronomical discoveries with Hubble from the solar system to the edge of the universe are among the most significant intellectual achievements of the space science program.

FINDING: The scientific power of Hubble has grown enormously as a result of previous servicing missions.

FINDING: The growth in the scientific power of Hubble would continue with the installation of the two new instruments, WFC3 and COS, planned for the SM-4 shuttle astronaut mission.

THE RISKS OF ROBOTIC SERVICING

Because a robotic servicing mission does not involve risks to the safety of an astronaut crew, the principal concerns are the risk of failure to develop a robotic mission capability in time to service Hubble, and the risk of a mission failure that results in an inability to perform the needed servicing, or worse, critically damages Hubble during the mission. Both schedule risk and mission risk are composed of a large number of factors that were studied in considerable detail by the committee.

Some of the critical components of mission risk include lack of adequate development time to validate the hardware, level of software and system performance required to rendezvous with Hubble, failure to successfully grapple and dock with Hubble, failure to successfully execute the combination of complex autonomous and robotic activities required to actually accomplish HST revitalization and instrument replacement, and the risk of unforeseen Hubble failures prior to mission execution that the robotic mission will not have been designed to repair. One example of a mission risk that concerned the committee is the complicated docking maneuver required for a Hubble robotic servicing, which has never been performed autonomously or teleoperated with time delays. Specifically, the use of the grapple system to autonomously perform close-proximity maneuvers and the final capture of Hubble is a significant challenge and is one of the key technical aspects of a robotic servicing mission that has no precedent in the history of the space program.

The components of schedule risk examined by the committee included the readiness levels of such technologies as the sensors, software and control algorithms, and vision-based closed-loop support for autonomous docking operations, as well as NASA's relevant programmatic and technical expertise, resources, and specific development plans for a robotic servicing mission. From the risk mitigation viewpoint, the committee judged that the planned use of the mature International Space Station robotic arm and robotic operational ground system helps reduce both the schedule risk and the development risk for the robotic mission. In addition, the committee assessed the development schedule for the robotic servicing mission based on its experience with programs of similar complexity and the historical spacecraft development schedule data provided by both NASA and the Aerospace Corporation. The committee's key findings regarding the question of the risk of robotic servicing are as follows:

FINDING: The technology required for the proposed HST robotic servicing mission involves a level of complexity, sophistication, and maturity that requires significant development, integration, and demonstration to reach flight readiness.

FINDING: The Goddard Space Flight Center HST project has a long history of HST shuttle servicing experience but has little experience with autonomous rendezvous and docking or robotic technology development, or with the operations required for the baseline HST robotic servicing mission.

FINDING: The proposed HST robotic servicing mission involves a level of complexity that is inconsistent with the current 39-month development schedule and would require an unprecedented improvement in development performance compared with that of space missions of similar complexity. The likelihood of successful development of the HST robotic servicing mission within the baseline 39-month schedule is remote.

Based on extensive analysis, the committee concluded that the very aggressive schedule for development of a viable robotic servicing mission, the commitment to development of individual elements with incomplete systems engineering, the complexity of the mission design, the current low level of technology maturity, the magnitude of the risk-reduction efforts required, and the inability of a robotic servicing mission to respond to unforeseen failures that may well occur on Hubble between now and the mission, together make it unlikely that NASA will be able to extend the science life of HST through robotic servicing.

THE RISKS OF SHUTTLE SERVICING

The risks that must be considered in making a decision to service Hubble with the shuttle are the risk to the safety of the crew and the shuttle, as well as the risk of failing to accomplish the servicing objectives. As part of its assessment of safety risk, the committee looked carefully at the findings and recommendations of the Columbia Accident Investigation Board (CAIB)[5] and at NASA's return-to-flight (RTF) requirements. Strong consideration was given to understanding differences in the safety risk factors between shuttle missions to the International Space Station (ISS)—to which NASA still plans to fly 25 to 30 missions—and a shuttle mission to Hubble. Technical considerations examined by the committee included comparisons of on-orbit inspection and repair capabilities at ISS and Hubble, various safe-haven and rescue options, and the likelihood of the shuttle being damaged by micrometeoroid and orbital debris (MMOD). With regard to mission risk, the committee considered both the known on-orbit operations required for Hubble servicing and past experience with Hubble shuttle astronaut servicing, including such factors as unforeseen on-orbit contingencies.

[5] Columbia Accident Investigation Board, *Report, Volume I,* August, 2003. Available online at http://www.nasa.gov/columbia/home/CAIB_Vol1.html.

The committee developed a large number of findings based on the various analyses cited above. Some of the key findings relevant to the question of the risk of shuttle servicing of HST are as follows:

FINDING: Meeting the CAIB and NASA requirements (relative to inspection and repair, safe haven, shuttle rescue, MMOD, and risk to the public) for a shuttle servicing mission to HST is viable.

FINDING: The shuttle crew safety risks of a single mission to ISS and a single HST mission are similar and the relative risks are extremely small.

FINDING: Previous human servicing missions to HST have successfully carried out unforeseen repairs as well as executing both planned and proactive equipment and science upgrades. HST's current excellent operational status is a product of these past efforts.

FINDING: Space shuttle crews, in conjunction with their ground-based mission control teams, have consistently developed innovative procedures and techniques to bring about desired mission success when encountering unplanned for or unexpected contingencies on-orbit.

FINDING: The risk in the mission phase of a shuttle HST servicing mission is low.

COMPARISON OF THE RISKS AND THE BENEFITS OF SERVICING

As noted above, the Hubble Space Telescope provides unique capabilities for astronomical research. These capabilities will not be replaced by any existing or currently planned astronomy facility in space or on Earth. Hubble's continuing and extraordinary impact on human understanding of the physical universe has been internationally recognized by scientists and the public alike.

Upgrading Hubble to address the predictable decline in HST component performance over time and thus ensure system reliability requires a timely and successful servicing mission in order to minimize further degradation and prevent a significant gap in science data return. Although it considered other options for servicing Hubble, the committee focused on two approaches: robotic servicing and shuttle astronaut servicing.

The need for timely servicing of Hubble imposes difficult requirements on the development of a robotic servicing mission. The very aggressive schedule, the complexity of the mission design, the current low level of technology maturity, and the inability of a robotic servicing mission to respond to unforeseen failures that may well occur on Hubble between now and a servicing mission make it unlikely that the science life of HST will be extended through robotic servicing.

A shuttle astronaut servicing mission is the best option for extending the life of Hubble and preparing the observatory for eventual robotic de-orbit by, for example, attaching targets to Hubble. The committee believes that a shuttle HST servicing mission could occur as early as the seventh shuttle mission following return to flight, at which point critical shuttle missions required for maintaining ISS will have been accomplished. All important systems needed to keep Hubble functioning well through 2011 were included in the original SM-4 shuttle servicing plan. Replacement of batteries and gyros and one FGS is deemed essential. Any spacecraft is subject to unanticipated failures, but if the repairs planned for the SM-4 mission are carried out promptly, there is every prospect that Hubble can operate effectively for another 4 to 5 years after servicing.

The committee finds that the difference between the risk faced by the crew of a single shuttle mission to ISS—already accepted by NASA and the nation—and the risk faced by the crew of a single shuttle servicing mission to HST, is very small. Given the intrinsic value of a serviced Hubble, and the high likelihood of success for a shuttle servicing mission, the committee judges that such a mission is worth the risk.

RECOMMENDATIONS

1. The committee reiterates the recommendation from its interim report that NASA should commit to a servicing mission to the Hubble Space Telescope that accomplishes the objectives of the originally planned SM-4 mission.
2. The committee recommends that NASA pursue a shuttle servicing mission to HST that would accomplish the above stated goal. Strong consideration should be given to flying this mission as early as possible after return to flight.
3. A robotic mission approach should be pursued solely to de-orbit Hubble after the period of extended science operations enabled by a shuttle astronaut servicing mission, thus allowing time for the appropriate development of the necessary robotic technology.

1
Introduction

BACKGROUND

The Hubble Space Telescope (HST) was launched aboard the space shuttle in 1990 and has operated continuously in orbit for the past 14 years. Over its lifetime, HST has been an unprecedented scientific success, having earned extraordinary scientific and public recognition for its contributions to all areas of astronomy. Hubble today is not the same telescope that was launched in 1990. A series of shuttle astronaut servicing missions, planned from the beginning of NASA's Space Telescope project in the late 1970s, has by now replaced, repaired, or upgraded many of the key components constituting the original telescope. Three of the four servicing missions contributed major new instrument observing capabilities. New observing modes were provided, and the efficiency of existing ones was increased dramatically. As a result, Hubble now produces much more data per unit time than it did originally.

Prior to the loss of the space shuttle Columbia and its crew in February 2003, planning was underway for a fifth shuttle servicing mission, designated SM-4, that would replace aging spacecraft batteries, fine-guidance sensors, and gyroscopes and would install two new science instruments on the telescope.

But in its August 2003 report, the Columbia Accident Investigation Board (CAIB), created to determine the cause of the Columbia accident and to advise NASA about steps to prevent future accidents, noted the inherent risk in any form of human spaceflight and made 29 recommendations, 15 of which it regarded as requirements to be completed before the space shuttle could return to flight.[1] The report made specific recommendations about on-orbit shuttle inspections and repairs, and it noted differences between future flights to the International Space Station (ISS), which could be used as a safe haven, and other possible destinations. NASA subsequently formed an internal committee, called the Stafford-Covey Return-to-Flight Committee, to provide oversight of the efforts to comply with the 15 recommendations of the CAIB that must be implemented prior to returning to flight. NASA Administrator Sean O'Keefe committed the agency to following the CAIB recommendations.

In mid-January 2004 O'Keefe announced that, as a consequence of safety considerations, NASA would reduce its shuttle manifest to only the 25 to 30 (the precise number of flights required is uncertain at this time) planned missions required to build the ISS. The decision was also made, on the basis of risk, to not pursue the Hubble Space Telescope SM-4, but instead to investigate other options for extending the life of HST. That announcement was followed by considerable expression of public concern in many media outlets about the future of Hubble, and astronomers and other scientists also raised many questions about the decision. Senator Barbara Mikulski (D-Maryland) asked O'Keefe to seek an independent opinion on whether the decision to cancel SM-4 was, in fact, required for compliance with the CAIB's recommendations. In response, O'Keefe asked the CAIB chair, Adm. Harold Gehman, to review the matter. In his March 5, 2003, letter to Mikulski, Gehman said that "the Board is split on the merits of flying this mission." He also indicated that "whether to fly another mission to the Hubble is one of the public policy debates this nation should have," and he called for a "deep and rich study of the entire gain/risk equation (to) answer the question of whether an extension of the life of [HST] is worth the risks involved."

Subsequently the National Research Council was asked to perform such a study. To do so, it appointed the Committee on the Assessment of Options for Extending the Life of the Hubble Space

[1] Columbia Accident Investigation Board, *Report, Volume I,* August, 2003. Available online at http://www.nasa.gov/columbia/home/CAIB_Vol1.html.

Telescope. This final report, together with an interim report released in July 2004,[2] represents the outcome of that effort.

GOALS OF THIS STUDY

The principal goal of this study is to assess options for extending the life of HST. The assessment considers issues of safety in the use of the space shuttle for servicing HST with an astronaut crew, the feasibility of robotic servicing approaches, the impacts of servicing options on HST's scientific capability, and risk/benefit relationships between servicing options that are deemed acceptable. The specific tasks addressed in the course of the study are listed in Appendix A.

During the development of the most recent decadal strategy for astronomy and astrophysics,[3] it was assumed that the Hubble SM-4 mission, long considered an integral element of the U.S. space astronomy program, would be conducted at the time necessary to prevent the demise of the telescope and to enable Hubble's ongoing operation for conducting astronomical research in the wavelength range covered by HST. The next major facility initiative in space astronomy given priority in the 2001 decadal strategy was the James Webb Space Telescope (JWST). The advisory panel convened by NASA in 2003 to advise it on the transition from HST to the JWST concurred with the decadal survey on the need for the SM-4 servicing mission and noted the work that had already been done, and was currently in progress, toward this servicing.[4] The advisory panel recommended that a servicing mission SM-5 also be pursued, but only "in a peer-reviewed competition with other new space astrophysics proposals."

In keeping with the statement of task given to the committee, this report does not address, or support, any changes in priorities for astronomical research or facilities. The committee assumed that NASA, in order to strive for frontier achievements in astronomy and astrophysics, would follow the 2001 decadal survey's advisory recommendations. If NASA concludes that it cannot move forward with portions of the decadal survey strategy, then NASA will have to carry out an examination of priorities for the research field. The committee does not endorse such a re-examination. The committee notes that if a re-examination should occur it would have to be conducted in a very timely and very expeditious fashion in order to ensure the continued operation and integrity of Hubble (see discussions in Chapter 4).

REPORT ORGANIZATION AND DEVELOPMENT

To address the various aspects of its task required that the committee engage in considerable analysis of a large volume of technical material and information provided in various briefings. Two key documents to which the committee referred frequently were the report of the Columbia Accident Investigation Board and a NASA document titled *NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond*.[5] In addition, the committee also had access to numerous additional reports and technical documents on topics ranging from the test data on Hubble battery recharging cycles to industry

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[2] See Appendix C, National Research Council, 2004, "Assessment of Options for Extending the Life of the Hubble Space Telescope," letter from Louis J. Lanzerotti, chair of the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope to Sean O'Keefe, NASA administrator, July 13. Available online at http://books.nap.edu/html/Hubble_Space_Telescope/letter_report.pdf

[3] National Research Council, 2001, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C.

[4] HST-JWST Transition Panel, *Report of the HST-JWST Transition Panel,* August 14, 2003. Available online at http://www.nasa.gov/pdf/49151main_hst-jwst.pdf.

[5] NASA, *NASA's Implementation Plan for Space Shuttle Return to Flight and Beyond*, Volume 1, Revision 1, October 15, 2003. This and subsequent revisions (2.1, July 28, 2004; 2.2, August 27, 2004) are available online at www.nasa.gov/news/highlights/returntoflight.html. During the course of this study, this document underwent a number of revisions, each of which was supplied to the committee.

proposals for the development of robotic missions.[6] The committee's work also benefited from the input of many experts at NASA and in academia and industry, who gave extensive briefings (listed in Appendix B), and from information received from many other individuals who made themselves available by telephone and e-mail to answer specific questions posed by committee members. The committee's analysis was limited by the dearth of data in some areas, such as the lack of a probabilistic risk assessment that took into account the differences in the safety risk of shuttle missions to ISS versus to Hubble, and the lack of detailed cost estimates for the SM-4 shuttle mission. A study by the Government Accountability Office (previously the General Accounting Office) being prepared for release in late 2004 assesses the costs of such a mission, and its findings are expected to be considered along with those of this committee when a decision is made regarding HST servicing.

Those issues that involved the most data, or required the most complex analysis, are treated in separate chapters of this report: (1) the scientific benefits of servicing Hubble, in Chapter 3; (2) the servicing needs and operational status of Hubble, in Chapter 4; (3) the prospects for Hubble servicing via a robotic mission, in Chapter 5; (4) the prospects for Hubble servicing via a shuttle mission, in Chapter 6; and (5) a discussion of the various types of risks involved in servicing Hubble, in Chapter 7. Although robotic servicing and shuttle servicing were the options to which the committee devoted the most time and energy, other options for extending the life of Hubble were considered, and discussion of these is included where appropriate throughout the report. Each section of the report contains findings relevant to the task statement. The final conclusions and recommendations of the study, stated simply in Chapter 8, derive directly from the findings and analysis presented in the preceding chapters.

[6] Return to Flight Task Group: *Interim Report,* January 20, 2004, available online at http://returntoflight.org/assets/pdf/report-01-20-2004.pdf, and *Second Interim Report,* May 19, 2004, available online at http://returntoflight.org/assets/pdf/report-05-19-2004.pdf.

2
Hubble Space Telescope

HUBBLE AS A SYSTEM

Conceptual discussions for a large space-based astronomical telescope date from the 1960s. Initially a 3-meter mirror with a stability of 0.003 arc second was considered. Because of cost and system complexity, the size of the primary mirror was changed in the mid-1970s to 2.4 meters with a stability of 0.007 arc second. Pivotal discussions then began within NASA on flying such a telescope, and an announcement of opportunity for "proposals for scientific investigations and related participation in the Space Telescope" was issued in March 1977. A memorandum of understanding between the European Space Agency (ESA) and NASA was signed in October 1977 for ESA participation in the NASA 2.4 Meter Space Telescope Project.

The design of the space telescope was begun in the late 1970s, with a launch by a space shuttle scheduled for 1983. Around that time, the name of the spacecraft was changed to the Hubble Space Telescope (HST) in honor of the famous astronomer Edwin Hubble. After delays that included those arising from the loss of the space shuttle Challenger in 1986, the telescope was finally launched in 1990. The HST has operated continuously since.

The Hubble telescope system was developed by the Marshall Space Flight Center in conjunction with its system and spacecraft contractor, Lockheed Missiles and Space Company, and optical system contractor Perkin-Elmer (later a part of Hughes Danbury, and now a part of the Goodrich Corporation; see Smith for details on the telescope's genesis, design, development, and launch;[1] see Logsdon[2] for reproductions of selected documents related to telescopes in space and the space telescope). Goddard Space Flight Center managed the science and operations development in support of the program. Hubble's structure and general avionics system are based on those of satellite systems of similar size and complexity that were developed by Lockheed and associated optical contractors in the 1970s and early 1980s. An exploded view of the telescope system is shown in Figure 2.1.

Hubble was designed with an anticipated 15-year lifetime based on the expected integrity of the main mirror. It was believed that over HST's 15-year life the space environment in low Earth orbit would cause sufficient degradation of the mirror that the telescope's light-gathering capabilities would be severely damaged by cosmic rays and orbital debris. To date, since the first shuttle servicing mission's correction for a significant aberration in the mirror, there has been no measurable degradation. The operations of the telescope over the 14 years since launch have provided an extensive database on HST's performance and failure mode and effects that can be used for engineering purposes to attempt to anticipate the spacecraft's future performance.

An important feature of Hubble is that it was the first spacecraft to be designed specifically for on-orbit servicing by astronauts. At the same time, however, the telescope's avionics subsystems, largely included in the Support System Module Equipment Section (see Figure 2.1), were not specifically designed to be accessible for servicing. These included such subsystems as the Data Management Unit, the Data Interface Unit, the Power Control Unit, and transponders. Even so, astronauts could change out some of these subsystems during servicing missions.

Most of the astronaut-serviceable subsystems were designed with the intention of change-out on an approximately 3-year cycle. The principal serviceable elements are, by design, located in equipment bays external to the main spacecraft or reachable via compartment doors specifically designed for access by astronauts. Hence, assumptions about the basic reliability of HST's major systems were predicated on

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[1] Smith, Robert W., 1993, *The Space Telescope: A Study of NASA, Science, Technology, and Politics,* Cambridge University Press, New York.

[2] Logsdon, J.M., ed., 2001, *Exploring the Unknown*, NASA History Series, NASA, Washington, D.C.

astronaut servicing at regular 3-year intervals. In addition, key engineering subsystems of Hubble were also designed for astronaut servicing intended to maintain the spacecraft's performance over its design lifetime. Such subsystems include the batteries, the solar arrays, the fine-guidance sensors, the gyroscopes, and the reaction wheels.

A key aspect of astronaut servicing of Hubble is that the capability to upgrade the astronomy science instruments on a regular basis has enabled the astronomy community to respond to new research opportunities and to utilize new technologies over the life of the facility.

After launch it was discovered that the telescope had a major optical flaw that resulted in operation at only 5 to 10 percent of its estimated capacity. In the first Shuttle Service Mission (SM-1), flown in December 1993, this flaw was corrected for by adding new instruments, including the new Wide Field Planetary Camera 2 (WFPC2), and adjustments were made to certain other instruments by adding the Corrective Optics Space Telescope Axial Replacement (COSTAR) module.[3] Three additional servicing missions conducted by shuttle astronauts have improved Hubble's capabilities and enhanced its reliability with no concomitant diminution of its performance. Table 2.1 summarizes the repairs and upgrades performed to date and the science impacts realized as a result of the four servicing missions by shuttle astronauts from December 1993 through March 2002.

Several of the activities listed in Table 2.1 were not planned but were instead repairs of opportunity that the on-orbit astronauts could make because of their ability to adapt to unplanned events. These repairs of opportunity are discussed further in Chapters 4 and 6.

Prior to the Columbia shuttle accident a fifth Shuttle Servicing Mission (SM-4) to Hubble was being actively planned. Long envisioned by NASA, SM-4 had been incorporated into the strategic planning of the nation's astronomy community. In particular, the most recent decadal survey of astronomy and astrophysics[4] assumed (because of NASA's plans) the existence of SM-4 for space visible and ultraviolet astronomy when the research strategy for the first decade of the 21st century was developed. In addition to needed servicing, replacements, and repairs, two major new instruments were scheduled to be flown on SM-4. These planned elements are listed in Table 2.2.

The planned SM-4 replacements and repairs would add to the science capabilities of HST (see Chapter 3) and ameliorate the overall degradation of Hubble as its subsystems age. Specifically, two new instruments planned for installation, the Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS), both now ready for flight, would add wide-field IR imaging, efficient UV imaging, and UV spectroscopy on Hubble. The batteries would also be replaced, as well as gyroscopes and a fine-guidance sensor. In addition, the aft spacecraft shroud cooling system would be replaced, and a New Outer Layer Blanket (NOBL) and a DSC (Data Management Unit (DMU) to Scientific Instrument (SI) Command and Data Handling (C&DH) Cross-Strap) would be installed. The installation of these subsystems would ensure continued telescope integrity and pointing accuracy, among other capabilities.

CURRENT STATUS OF HUBBLE

Following its decision to cancel the SM-4 mission, NASA announced that it plans to continue HST's operation until the observatory can no longer support scientific investigations, currently anticipated to occur around 2007 to 2008,[5] depending on the success of certain planned efforts to preserve battery and gyroscope functions. Meanwhile, NASA is investigating methods of extending HST's science lifetime, including the use of robotic servicing. If all else fails, NASA's current plans are to de-orbit HST by means of a robotic spacecraft by approximately 2013.

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[3] Instruments corrected by the addition of COSTAR were the Faint Object Camera (FOC), the Faint Object Spectrograph (FOS), and the Goddard High Resolution Spectrograph (GHRS).

[4] National Research Council, 2001, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C.

[5] See Figure 4.3 in Chapter 4.

TABLE 2.1 Hubble Telescope Shuttle Servicing Missions

Servicing Mission	New Instruments Installed[a]	Major Repairs[a]	Science Impacts
SM-1 Dec. 1993	WFPC2, COSTAR RSU (2), ECU (2)	Mirror aberration corrected; repairs to solar arrays, gyroscopes, GHRS kit, SADE, magnetometer (2), fuses	Nominal performance achieved
SM-2 Feb. 1997	NICMOS, STIS OCEK, ESTR-2 FGS-1R	RWA-1R, DIU-2R, SADE 2R, MSS covers, MLI patches, SSR	Capability for infrared imaging, long-slit spectroscopy
SM-3A Dec. 1999	FGS-2R+ OCEK, RSU-3	Emergency repair of gyroscopes, advanced computer, SSAT-2R, MLI, NOBL	Capabilities maintained
SM-3B Mar. 2002	ACS	RWA-1R, PCU, NCS, MLI, fuses, rigid solar arrays	Wide-field visible imaging enabled; infrared imaging restored

[a] See Appendix E for definitions.

TABLE 2.2 Elements of Planned Shuttle Servicing Mission 4 (SM-4) to the Hubble Space Telescope

Mission	Instruments[a]	Major Repairs[a]	Science Impacts
SM-4	WFC3, COS	FGS-2R, 3RSUs, 3 batteries, OCE, DSC ASCS, NOBL	Five-year life extension, wide field IR imaging, enhanced UV imaging, and spectroscopy

[a] See Appendix E for definitions.

The telescope uses three gyroscopes to provide precision attitude control. There are currently four functional gyros on HST—three in operation plus one spare. As discussed in detail in Chapter 4, it is likely that the HST system will be reduced to two operating gyros in the latter half of 2006. The HST engineering team is currently working on approaches to sustaining useful astronomical operations with only two gyros, and the team expects to have that capability by the time it becomes necessary. Two-gyro testing is scheduled to begin in March 2005. There are hopes that even a one-gyro operation mode might be feasible for limited telescope operations, but there are no detailed plans for this mode. The spacecraft can be held in a safe configuration with no operating gyros, but science operations would not be possible.

As is also discussed in detail in Chapter 4, battery failures are another likely cause of loss of science operations. HST now has six batteries, of which five are necessary for full operations. If battery levels fall too low, the temperature of structural elements in the Optical Telescope Assembly will fall below permissible levels, causing permanent damage.[6] Recovery from this state is not possible.

A recent development is the failure on HST of the Space Telescope Imager and Spectrograph, a powerful ultraviolet/visible imager and spectrograph whose Side B electronics failed in August 2004 (side A had failed earlier). The cause of the failure appears to be understood, and investigations are underway to understand the feasibility, if any, of a repair.

Details of the current status of the observatory are provided in Chapter 4.

[6] Some of the electronics system components will also exceed their thermal qualification limits and may be damaged in this unpowered condition.

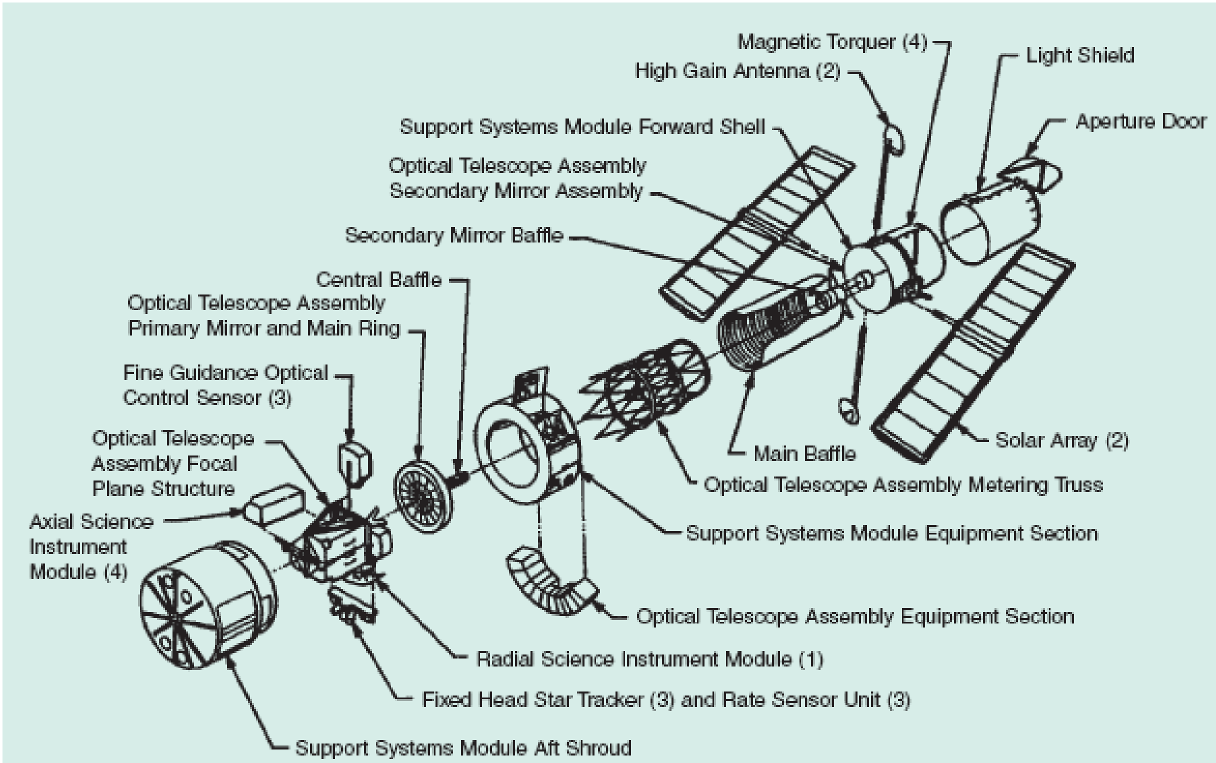

FIGURE 2.1 Exploded view of the Hubble Space Telescope and its major subsystems.

3
The Impact of Hubble: Past and Future

OVERVIEW

The Hubble Space Telescope (HST) is arguably the most powerful single optical astronomical facility ever built. Hubble provides wavelength coverage and capabilities that are unmatched by any other optical telescope currently operating or planned, and there is nothing on the horizon to replace it. Hubble is a uniquely successful NASA science program and is a national asset well worth maintaining in operation.

The Hubble telescope provides four key advantages over most other optical astronomical facilities: unprecedented angular resolution over a large field, spectral coverage from the near infrared to far ultraviolet, an extremely dark sky, and highly stable images that enable precision photometry. Hubble's imaging fields of view are also considerable, permitting mapping of extended objects and significant regions of sky.

Unlike standard ground-based telescopes,[18] whose view is blurred by the atmosphere and wholly impeded in the ultraviolet and large portions of the near infrared, Hubble can see sharply and clearly at all wavelengths from the far ultraviolet to the near infrared (Figure 3.1). Hubble images are five to twenty times sharper than those obtained from the ground, in effect bringing the universe that much "closer" (Figure 3.2). Image sharpness and the extremely dark sky help Hubble to see objects ten times fainter than even the largest ground-based telescopes. Moreover, Hubble's images are extremely stable, in contrast to those of standard ground telescopes, where changing atmospheric clarity and turbulence continually distort the view. Singly, each of these advantages would be a significant advance for science. Coupled together they have created the most powerful astronomical facility in history. Hubble is a general purpose national observatory that provides unique contributions and insights to most astronomical problems of greatest current interest.

Of course, Hubble cannot do everything. It is not sensitive to very high-energy radiation like x-rays and gamma-rays, or to low-energy radiation in the mid- and far-infrared or radio regions. It cannot collect the sheer quantity of light available to larger ground-based telescopes, which is vital for obtaining high-resolution spectra. To fill these important gaps, Hubble must work synergistically with other telescopes to complete the portraits of celestial objects at all wavelengths.

FINDING: The Hubble telescope is a uniquely powerful observing platform because of its high angular optical resolution, broad wavelength coverage from the ultraviolet to the near infrared, low sky background, stable images, exquisite precision in flux determination, and significant field of view.

The Hubble telescope is presently equipped with a selection of cameras operating at different wavelengths, as summarized in Table 3.1. The Space Telescope Imager and Spectrograph (STIS) failed in 2004, but several of its ultraviolet modes would be replaced with the installation of Cosmic Origins Spectrograph (COS) during a servicing mission. A flexible mix of wavelengths, spectral resolutions, and field-of-view sizes is a key element of Hubble's power.

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[18] Ground-based telescopes equipped with adaptive optics are discussed in "Comparison of Hubble with Other Planned Facilities" in Chapter 3.

TABLE 3.1 Principal Hubble Science Instruments

Instrument	Wavelength Range (micron)	Pixel Size (arc sec)	Field of View (arc sec)
Existing:			
ACS/Wide field	0.35–1.05	0.1	205 × 205
ACS/High-resolution	0.20–1.05	0.026	26 × 26
NICMOS/NIC1	0.8–1.8	0.043	11 × 11
NICMOS/NIC2	0.8–2.5	0.075	19 × 19
NICMOS/NIC3	0.8–2.5	0.20	51 × 51
WFPC2/Wide field	0.12–1.05	0.1	3 × 75 × 75
WFPC2/Planetary	0.12–1.05	0.046	35 × 35
Planned for SM-4:			
WFC3/UV, visible, near IR	0.20–1.05	0.04	160 × 160
	0.80–1.70	0.13	135 × 135
COS spectrograph	0.12–0.32		

OBSERVING WITH HUBBLE

Hubble observing is open to the worldwide astronomical community, and astronomers compete fiercely to win time on the telescope via their scientific proposals. Independent peer review of the proposals is the basis of the science selection program by the Space Telescope Science Institute (STScI), and chosen programs cover the entire range of astrophysics. Requested time typically exceeds that available by a factor of about seven. This oversubscription rate has remained essentially constant over the lifetime of the telescope, and is about twice that of large U.S. ground-based telescopes.

Selection among the wealth of excellent proposed programs is done by panels of astronomers with significant international representation. In the most recent cycle, some 100 scientists participated in the review process. Two hundred proposals were selected, authored by 955 U.S. astronomers and 358 from 13 other countries. Many of the successful proposers were graduate students and postdoctoral fellows, making Hubble one of the most important astronomical training resources in the world. Roughly 60 percent of the grant funding in a typical proposal cycle (e.g., Cycle 12) goes to postdocs, fellows, and graduate students.

Observations are scheduled by the STScI based on detailed instructions from the proposers. Data that are acquired are proprietary to the investigators for a twelve-month period, after which they become public in the HST Archive. Hubble has led the way in making astronomical archives accessible, and the archive is nearly as popular for analyses as are new data, as each Hubble observation can be re-used many times by new investigators for new projects. The archive presently boasts 1,500 registered users and 19 terabytes of data. Its value keeps growing as new data arrive, and its total impact has increased the productivity of the telescope greatly. The data archive will be one of the most enduring elements of the telescope's legacy.

For successful U.S. proposers, an award of Hubble observing time carries with it a monetary grant to support the scientific research. This money pays for the salaries of researchers, stipends for students and postdoctoral fellows, computers, and publication costs. The annual HST Grants Program in Cycle 13 (the current cycle) is approximately $20 million, an appreciable fraction of the entire budget for university grant programs and fellowships in all disciplines and wavelengths in the Astronomical Sciences Division at the National Science Foundation (approximately $31.5 million).

SCIENCE HIGHLIGHTS

The Space Telescope Science Institute has studied the scientific impact of Hubble observations using two metrics: the number of citations in the professional astronomical literature and references to Hubble discoveries in the popular media. Table 3.2 lists the top ten Hubble contributions based on astronomical citations, and the following text expands on five representative examples from the list.

Ultradeep Images of the Universe—Galaxies in Formation

Hubble looks so far out into space that it takes many billions of years for light from those distant objects to reach us. We therefore see these objects as they were at some distant time in the past; in effect, Hubble provides a "time machine" that can show us how the universe evolved. The Hubble Ultradeep Field penetrates back more than 12 billion years to within 1 billion years of the Big Bang (Figure 3.3). Infant galaxies can be seen in the process of forming, harbingers of a great wave of star formation that soon afterwards bathed the universe in the light of ten billion trillion stars and the major stages in the history of galaxy formation are accessible to direct observation.

Measurement of the Hubble Constant, the Distance Scale of the Universe

The size and age of the universe have long been uncertain by a factor of two, and this uncertainty has been a major obstacle to the testing of cosmological theories. Hubble has measured the apparent brightness of so-called "Cepheid variable" stars in nearby galaxies and used them to estimate the distances to those galaxies. This procedure provided an accurate value for H_0, the Hubble constant, thereby calibrating the distance scale and size of the universe.

Giant Black Holes at the Centers of Galaxies

Hubble's high angular resolution allows astronomers to peer into the hearts of galaxies to measure the orbital speeds of gas and stars close to their centers. The speeds of stars reach 1000 km/s in many objects, thereby indicating the presence of intense gravitational fields caused by massive black holes of up to a billion solar masses. Though mostly invisible today, these black holes shone brilliantly in the past as quasars, fueled by the infall of then-abundant interstellar gas. Key data found by the Hubble telescope reveal a correlation between black hole mass and galaxy properties that may provide crucial clues to how and why these holes formed.

TABLE 3.2 Top Ten Hubble Contributions

Observation or Result	Significance
Ultradeep images of the distant universe	Shows the formation of galaxies and confirms that the universe evolves. Tells the story of how our Milky Way was born.
Accurate measurement of the Hubble constant, H_0	Establishes the size and age of the universe.
Discovery of giant black holes at the centers of galaxies	Confirms longstanding theory of the “central engines” of quasars.
Confirmation of accelerated expansion of the universe	Requires the existence of “dark energy.”
Discovery of spectral lines in active galaxies	Reveals that black holes can trigger massive star formation.
Expansion of the census of the intergalactic medium	Establishes existence of a web of invisible matter filaments linking galaxies over hundreds of millions of light-years and controlling the matter-energy budget of the universe.
Importance of chemistry of the interstellar medium	Formation and distribution of the chemical elements; physical state of the gas in interstellar space.
Identification of gamma-ray bursts with distant galaxies	Confirms that sources of gamma-ray bursts lie at cosmological distances and that gamma-ray bursts (during their brief flashes) are the brightest objects in the universe.
Resolved images of proto-planetary disks	Reveals flattened, rotating disks of dust and gas that almost certainly resemble our own solar system in its infancy.
Studies of extrasolar planets	Offers a sensitive method for finding planets around other stars, based on partial eclipses when a planet passes in front of a distant star.

Accelerated Expansion of the Universe—Dark Energy

Einstein’s theory of general relativity says that gravity should slow the expansion of the universe. Hubble data, when coupled to those from other telescopes, show to the contrary that the expansion is accelerating and that galaxies move apart ever faster with time. This observation can be reconciled with general relativity only by invoking a new kind of energy density that remains constant despite the dilution expected from expansion. This so-called dark energy is unlike ordinary matter or energy in that it generates a repulsive gravity that is literally blowing the universe apart. Discovery of this fundamentally new cosmic entity is considered by many physicists to be the most important milestone in physics since the advent of general relativity and quantum mechanics in the early 1900s.

Protoplanetary Disks—Planetary Systems in Formation

Many luminous nebulae are dense regions of interstellar gas lit up by ultraviolet radiation from newly born massive stars. In the nearest such nebulae in our Galaxy, Hubble’s high resolving power has uncovered a cornucopia of proto-solar systems seen as dark, flattened disks silhouetted against the glowing background of nebular gas (Figure 3.4). At the centers of such disks, young suns can be seen in the process of formation. Powerful jets of plasma and magnetic fields are spewed out from some of these disks by a magnetic propulsion mechanism not yet fully understood. The discovery of proto-solar systems and energetic phenomena in nearby glowing nebulae has turned them into goldmines for studying the formation of stars and planets—including, by analogy, that of our own solar system.

HUBBLE IN THE SCIENTIFIC AND POPULAR PRESS

Nearly 5000 scientific papers have been published based on Hubble observations, and the publication rate in refereed journals is currently about 500 per year. Except possibly for the Chandra X-ray Observatory, which rivaled Hubble in terms of papers published in 2003, Hubble outstrips all other telescopes by more than a factor of two in both the quantity of papers published and the rates at which they are cited (Figure 3.5).

The importance of Hubble science is clear to all—one need not be a trained scientist to know that unveiling the birth of stars and galaxies, finding billion-solar-mass black holes, and helping to discover an entirely new form of energy in the cosmos are ground-breaking milestones in the history of science. But fundamental science is not the only way to judge Hubble's achievements. To the list of science highlights can be added an even longer list of spectacular images that, though not necessarily in the top 10 scientifically, have had extraordinary public impact by virtue of their sheer beauty or arresting novelty (Figure 3.6). Among these one might list the big "black eye" left by comet Shoemaker-Levy's direct hit on Jupiter, an image that alerted the public to the dangers of asteroids and comets hitting Earth; a panoply of jewel-like planetary nebulas that illustrate the ultimate death of our Sun; portraits of planets in our solar system including auroras on Jupiter and Saturn; and, of course, the spectacular "pillars of dust" in the Eagle Nebula that appeared on nearly every front page in America and became iconic for Hubble itself. Intense public interest in Hubble is borne out by many media studies, an example of which is shown in Figure 3.7. The Hubble Space Telescope is clearly one of NASA's most noticed science projects, garnering sustained public attention over its entire lifetime. In effect, Hubble has become a model to show how NASA can combine its own unique expertise with that of scientists to educate the public about the natural world.

FINDING: Astronomical discoveries with Hubble from the solar system to the edge of the universe are one of the most significant intellectual achievements of the space science program.

SCIENCE IMPACT OF HUBBLE SERVICING MISSIONS

Hubble today is not the same telescope that was launched in 1990. A series of servicing missions, summarized in Table 2.1 has repaired many key components, added new observing modes, and increased existing capabilities, typically by factors between 10 and 100. As a result, Hubble now produces much more data per unit time than it did originally. If the total data rate summed over all instruments can be taken as a rough measure of spacecraft productivity, Figure 3.8 shows how science data volume increased at each of the three servicing missions that added science instruments. The total rate of calibrated data has grown by a factor of 33 since launch. A further increase is expected with the installation of WFC3 and COS, each of which will provide a factor of more-than-10 improvement in scientific efficiency and sensitivity with respect to previous instruments.

FINDING: The scientific power of Hubble has grown enormously as a result of previous servicing missions.

The efficiency of a science instrument is a measure of the time needed to make a given observation, e.g., doubling the efficiency halves the time. Efficiency on Hubble has risen by orders of magnitude by increasing the size of detectors and by improving total optical throughput, and would increase further with the installation of two new instruments on SM-4. Wide field Camera 3 (WFC3) is an imager with two separate arms operating in the ultraviolet-visible and the near infrared. With more sensitive detectors and larger fields of view, it affords a gain of 10 in efficiency at 0.17–0.30 microns, and a gain of 50 at 0.80–1.7 microns. These numbers are huge for astronomy: for example, doubling the diameter of a ground-based telescope gives an efficiency gain of only 4, yet even this is highly sought after. Science programs that exploit the gain of WFC3 are indicated in Figure 3.9.

The second instrument to be installed by SM-4 is the COS. COS is a moderate-resolution ultraviolet spectrograph that achieves large efficiency gains of 10 or more over STIS by virtue of a more sensitive, larger detector, a reduction in background noise, and an improved optical design with much higher throughput. This last is possible because COS is optimized for a small but very important group of cosmological problems (see below). COS is even more important if STIS, the other moderate-resolution spectrograph, cannot be repaired—because COS can substitute to some degree for the UV arm of STIS.

FINDING: The growth in the scientific power of Hubble would continue with the installation of the two new instruments, WFC3 and COS, planned for SM-4.

DETERIORATING CAPABILITIES THAT AFFECT HUBBLE'S SCIENCE PERFORMANCE

Several Hubble subsystems have limited life and were to be serviced on SM-4. Chapter 4 presents a comprehensive review of these systems and establishes overall norms for spacecraft performance. This section discusses two of these systems in particular—gyros and fine guidance sensors (FGSs)—as their status bears particularly on the quality of the data that Hubble can return. The status and projected lifetimes of the science instruments are also reviewed.

- *Gyros.* Rate-Sensing Units and their associated electronics (collectively known as "gyros") are used to slew the telescope and to maintain highly accurate pointing during science exposures. Normal observing requires three working gyros. Presently there are three gyros operating, with one held in reserve. Based on the gyro reliability assessment discussed in "rate sensor unit (Gyroscope) Assessment" in Chapter 4, it is expected that Hubble will enter two-gyro mode in early 2006 (see Chapter 4), and plans are being made to operate the telescope that way. This transition will not greatly impact overall science productivity: increased pointing jitter will smear images somewhat in the highest-resolution modes, but the workhorse, wide-field modes will be affected only slightly. It will be more difficult to schedule observations because a much smaller portion of the sky will be accessible to the telescope at any one time, and a few targets may become totally inaccessible. However, the impact of two-gyro mode on science is mainly inconvenience rather than loss.

The effects of dropping down to a one-gyro mode are not well understood but could be severe. Given this uncertainty, the committee believes that it is prudent to assume that a one-gyro mode will result in a considerable drop in scientific output. This status is likely to occur in mid-2007 (see Chapter 4), providing a natural time frame for any servicing mission.

- *Fine-Guidance Sensors.* Fine guidance sensors are necessary to maintain accurate pointing during an observation; they line up on bright "guide stars" near the target. The telescope has three of these sensors any two of which are normally used for each observation. Three are needed to ensure that at least two can find guide stars any time. If one FGS fails, two options are available. The first would force the spacecraft to roll at each pointing so that the two remaining FGSs can find guide stars; this would place restrictions on scheduling and would probably render some astronomy targets permanently unobservable. Nevertheless, the spacecraft would still be very productive. The second option would be to devise a way to observe some targets with only one FGS; this presently causes a degradation of image quality, but workarounds are under study to reduce image smear by using either an idle science detector or a Fixed Head Star Tracker as a substitute FGS. These studies have not progressed very far to date, and success is not assured. If two of the three FGSs failed, it would be necessary to observe in single-FGS mode all the time, a very risky prospect at the present time.

The conclusion is that it is necessary to maintain a minimum of two out of three FGS units operational through the end of the Hubble mission. Currently, two out of three FGS units are degraded, and their times of failure can be estimated. As discussed in Chapter 4, this implies that one FGS unit should be included in the servicing mission. The shuttle version of SM-4 includes such a unit, but the baseline robotics mission does not.

- *Science instruments and related systems.* Information on degradations that potentially affect science instrument performance is summarized in Table 3.3. As noted, Side B of the STIS electronics failed in August 2004, and its repair is currently under study. The failure of STIS illustrates why redundancy is so important to spacecraft health—at its time of failure, STIS was one of only two non-redundant science instruments on the telescope, Side A having failed two years earlier. The failure was therefore in some sense foreseeable. The NICMOS cooler is also non-redundant, but the lowest-resolution, workhorse mode of NICMOS (NIC3) would be replaced by the WFC3 IR channel (although the two higher-resolution NICMOS modes would still be used). No other instruments exhibit serious problems or non-redundancies that imperil their functioning through 2011, although radiation damage to ACS and WFPC2 is causing the charge transfer efficiency for their detectors to decrease and the number of hot pixels to increase, leading to uncertainties of a few percent in their photometry by the end of the period. WFPC2 would be removed in SM-4 to make room for WFC3, so its condition would then become irrelevant, but ACS, which is a workhorse camera with the largest field of view, would continue to operate. For this reason, early servicing is desirable to minimize the accumulating radiation damage. No servicing of ACS or NICMOS is planned in SM-4.

Two other systems potentially affect the thermal health of the science instruments. These are the Aft Shroud Cooling System and the New Outer Blanket Layer, an outer insulation layer. Both of these are included in the shuttle version of SM-4 but not in the baseline robotics mission. These systems are discussed in Chapter 4, where it is decided that they are desirable but not essential for instrument functioning.

To summarize, with the exception of STIS, all important items needed to keep Hubble functioning well through 2011 are included in the shuttle SM-4 servicing plan. Replacement of batteries and gyros and one FGS is deemed essential. Any spacecraft is subject to unanticipated failures, but if the repairs envisioned for SM-4 are carried out promptly, there is every prospect that Hubble can operate effectively for another 4 to 5 years after servicing.

TABLE 3.3 Deteriorating Capabilities of Hubble Systems That Affect Scientific Operations

System	Current Status and Planned Fix	Science Impact
STIS	Side A electronics failed in 2002; Side B electronics failed in August 2004; feasibility of Side B repair under study.	With loss of redundancy, Hubble now has no moderate-resolution spectrograph.
Batteries	Charge capacity is decreasing; SM-4 would replace.	All science operations will cease when batteries fail.
Gyroscopes	Reduction to two functioning gyros likely by early 2006, one gyro by mid-2007; new gyros to be installed during SM-4.	Nominal operations require three gyros. Two-gyro mode will degrade highest-resolution images slightly and reduce target visibility; no proven workaround for one-gyro mode.
Fine guidance sensors	Some degradation in two of the three currently available FGSs; one is predicted to fail between 2007 and 2009, leaving two without redundancy.	Two-FGS mode will reduce target visibility and scheduling efficiency; no proven workaround for one-FGS mode.
ACS	Charge-transfer efficiency is gradually degrading, and “hot pixels” are increasing; no plan to service during SM-4.	Degradation significant but not expected to be serious until after 2011.
NICMOS	Cooling unit is nonredundant mechanically; no plan to service during SM-4.	NIC3 becomes backup when WFC3 is installed. High-resolution NIC1 and NIC2 modes will be lost if cooler fails.
WFPC2	Charge-transfer efficiency is degrading; to be replaced by WFC3 during SM-4.	Degradation not important if WFPC2 is replaced by WFC3.

THE PROMISE OF FUTURE DISCOVERIES

What important science programs would be enabled if Hubble’s life were extended? This essential question is examined here, starting with programs that could be done with the existing instruments, and proceeding to those depending on WFC3 and COS. It is important to note that typically only about ***half*** of all major discoveries made with new astronomical facilities are foreseen, while the other half are serendipitous. Hubble has been no exception in this regard—only five of the contributions listed in Table 3.2 were foreseen. Space also permits listing only a small faction of the science projects likely to be undertaken. For both reasons, the following list provides only a lower limit to the future discovery potential of Hubble.

One of the most active and exciting frontiers in astronomy in coming decades will be the discovery and study of extra-solar system planets. Finding planets, especially down to Earth-like size, has become an official goal of NASA. More than a hundred extra-solar planetary systems have been discovered (by ground-based telescopes), and they are very different from the solar system. Planets similar in mass to Jupiter have been found, but they are very close to their parent stars and often in highly elliptical orbits—not at all like the giant planets Jupiter, Saturn, Uranus, and Neptune that all orbit far from the Sun in nearly circular orbits. Given an example of exactly one solar system—ours—theorists had invented tidy theories that predicted that its structure was inevitable. The new discoveries have overturned these ideas, and the field of solar-system formation is now in ferment.

A rapidly developing technique for finding planets detects them as they transit across the face of their parent star and block a small part of the light.

The great advantage of Hubble for transit photometry is its extraordinary photometric stability, which allows it to detect much smaller decreases in light than can be measured through the Earth's fluctuating atmosphere. This is evident in Figure 3.10, where the scatter of the measurements is only 0.02 percent, some 50 times smaller than is possible with typical ground-based photometry. This scatter is only a factor of two larger than the dip caused by the Earth as it passes in front of the Sun, as seen by a hypothetical distant observer. HST's high accuracy is important to this effort in three ways. The first is illustrated in Figure 3.10, where HST actually resolves the time needed for ingress and egress. This is the only known way to measure planet radii. The second is to provide rapid confirmation for NASA's Kepler mission,[19] which is planned for launch in late 2007 and is specifically designed to search for transiting extra-solar planets, including Earth-like planets. The Kepler technique will produce many false positives that will need to be screened out by other methods. Kepler can do much of this itself, but the process will take years for Earth-sized candidates; high-resolution Hubble photometry could provide much more rapid feedback and possible optimization of further Kepler observations. For maximum benefit, Hubble operations should overlap Kepler from 2008 to beyond 2010. Finally, Hubble can take exceptionally accurate spectra of planetary systems during eclipse, yielding the measurement of water and other species in Jovian-sized planetary atmospheres.[20]

Photometry with JWST will also have higher accuracy than possible from ground-based telescopes and will also play an important role in planet detection. However, its system is not as well understood at this time, and its launch is still several years away. Similarly, most of Kepler's stars are too faint for effective imaging with ground-based adaptive optics systems. For proven high accuracy and overlap/coordination with Kepler, Hubble is preferred.

Besides extra-solar planets, a great variety of other important work will be able to continue if Hubble remains operational. A large number of new supernovae could be found to study dark energy, reducing uncertainties in its properties by a factor of two. A wealth of data would be taken to explore the nature of stars in the Milky Way Galaxy and in neighboring galaxies. Hubble is just beginning to image objects being found by sister NASA missions such as Chandra (an x-ray observatory), GALEX (an ultraviolet imager) and Spitzer (infrared imager and spectrograph), which are currently in orbit. These satellites are relatively wide-field survey telescopes, one of whose expressed purposes is to detect objects for Hubble follow-up observations. The chance for these follow-ups would be severely limited if Hubble's life were curtailed because the areas of the sky surveyed by Hubble for any one observation are much smaller than those observed at other wavelengths, and thus it requires more time to cover a field.

In the closing years of the Hubble telescope's active life, emphasis is turning toward the gathering of large, homogeneous data sets—including spectral libraries and imaging surveys of large areas within the Milky Way, nearby galaxies, and the distant universe. These data sets, called Treasury Programs, will go into the data archive; they are Hubble's "lay-away plan" for the future. These programs are extremely important because there are no plans in the foreseeable future to replace Hubble with a telescope of comparable size and wavelength coverage. The servicing mission SM-4 is needed allow an orderly completion of this important aspect of Hubble's mission.

Forefront programs would be enabled by the two new instruments to be installed by SM-4—starting with the near-infrared arm of WFC3. Long-wavelength imaging has been a popular mode on Hubble, but the relatively small field of view of the NICMOS camera has been a serious handicap. Important new vistas would be opened by the near-IR arm of WFC3. A major goal is observing the most distant galaxies, whose light is highly red-shifted by the expansion of the universe. Light from the most distant galaxies detectable by Hubble is red-shifted so much that it is "too red" for ACS, whose sensitivity ends at about 1 micron. Critical spectral features needed to measure age and distance and are red-shifted

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[19] Available online at http://www.kepler.arc.nasa.gov/.

[20] David Charbonneau, "Hubble's view of transiting planets," in *From Planets to Cosmology: Essential Science in Hubble's Final Years,* STScI 2004 May Symposium, Space Telescope Science Institute, Baltimore, Md., in press.

entirely out of ACS's range. WFC3 will reach these objects and enable Hubble at last to see the full distance to which its mirror is capable.

The deepest image taken yet with Hubble is its Ultradeep Field, in which a handful of objects have been identified beyond a redshift of 6 (see Figure 3.3). The age of the universe at this redshift is already 1 billion years; WFC3 images of the same field should reach back to redshift 10, nearly twice as close to the Big Bang. This is critical because the universe evolved rapidly at these epochs, and even a small increase in lookback time can reveal new phenomena. This is the era of the first galaxies, when stars began shining and black holes began to evolve toward quasars, when the featureless cosmic void began to condense and lay the foundations for planets and life. WFC3 looks through a window that will shed light on our own distant past.

How and when galaxies form stars is another great astronomical mystery. Much of the early star formation seems to have occurred in bursts triggered by massive galaxy collisions. Such bursts are hidden within dark clouds of gas and dust and cannot be seen at visible wavelengths. WFC3's near-infrared detector can penetrate the dust to reveal underlying properties of the starburst (see Figure 3.11). In this quest, WFC3 will work synergistically with the Spitzer infrared satellite, which will detect dust-enshrouded starbursts in great numbers but will rely on Hubble for high-resolution follow-up work.

A third important task of WFC3 is to pursue and extend the supernova discovery program. These objects have provided the best evidence that the universe is expanding faster with time, requiring dark energy to drive the acceleration. WFC3 could establish whether the amount of dark energy is evolving with time, or has remained constant—potentially an extremely important question for fundamental physics. Even without WFC3, Hubble would make progress by likely discovering some 30 new supernovae in 4 years. WFC3 would increase this detection rate by a factor of 2.5, and should also detect some extremely important supernovae at much larger distances. Such distant supernovae are invisible now, but should be detected in significant numbers by WFC3. The result would be much tighter constraints on the properties of dark matter.

Other programs for the WFC3-IR camera will include a hunt for water-bearing rocks on Mars and ices on outer satellites in the solar system. In each case, capabilities provided by Hubble will be unique among existing astronomical facilities.

Because the Earth's atmosphere is opaque to wavelengths less than 0.30 microns, the Hubble telescope offers unique opportunities at ultraviolet wavelengths. This potential has been only partly realized to date, because of the difficulty of making space-qualified ultraviolet detectors. High UV efficiency will be achieved on Hubble for the first time when both WFC3 and COS are installed. WFC3's short-wavelength detector will provide sensitive ultraviolet imaging below 0.30 microns. Stellar populations redden as they age, as hot, blue, massive stars die away. Slicing the spectrum into colors thus slices the stellar population into age cohorts, with the youngest, most recently formed stars visible in the ultraviolet. It will be exciting to turn WFC3's UV capability onto distant galaxies, whose star-formation histories can be captured at previous epochs and merged to synthesize the history of cosmic star formation.

While detecting radiation is usually the goal, sometimes *not* detecting it is even more important. Imaging at ultraviolet wavelengths can reveal the presence of distant proto-galaxies because light at wavelengths below 0.12 microns is absorbed by intervening clouds of intergalactic hydrogen gas, thereby creating a "hole" in the spectrum where it appears black. In distant objects, this hole is redshifted to longer wavelengths, so that objects disappear or "drop out" in certain colors. WFC3's greater UV sensitivity will allow it to discover UV dropouts nearly 10 times fainter than those presently known, deepening our knowledge of distant galaxies beyond the brightest ones currently known.

The other instrumental gap in the ultraviolet—spectroscopy—will be significantly filled by the Cosmic Origins Spectrograph. COS is an instrument optimized for a number of highly important programs in cosmology. The first of these is study of the "cosmic web" consisting of diffuse matter not yet coalesced into galaxies (Figure 3.12). The cosmic web forms a huge network in space around our Galaxy, but is largely invisible because no stars or galaxies have yet formed in it. It contains many vital clues to cosmogenesis. The density and geometry of the web reflect the original density ripples in the universe that gave rise to all the structure seen today. Galaxies form at "nodes" in the web, where filaments intersect and grow via the pull of gravity, which drags matter along web-lines into the nodes. How and when does this happen, and how do galaxies "turn on"? If it were visible to the eye, the web would reveal the distribution of matter that has not yet fallen into galaxies—which is most of the matter in the universe! The web is thus the dominant player in the cosmic matter-energy budget.

With COS it will be possible to study the cosmic web in detail for the first time. Though not radiating much by itself, the web absorbs light from bright, background sources such as quasars, leaving dips at particular wavelengths in the spectrum. Each quasar line-of-sight is thus a "core-drilling" through space that reveals pieces of the cosmic web. The big advantage of COS is higher sensitivity, some 10-30 times that of STIS. As a consequence, many more faint quasars can be studied, making a much denser pattern of core-drillings through space. The dense coverage should reveal the geometry of the web and its evolution with time.

The total observing program of COS will be rich because the same spectral features that delineate the web are also found in interstellar gas and in stellar atmospheres. The tracer elements involved include nitrogen, silicon, aluminum, oxygen, carbon, and iron—elements basic to the formation of Earth and life. COS spectra can be used to explore the chemical evolution of galaxies and the intergalactic medium via nucleosynthesis of these elements. Velocities of gas clouds can be measured to show how hot stars and quasars feed back their energy into surrounding gas, driving massive "winds" from galaxies. These UV spectral features are also important for studying the chemistry and physics of planetary atmospheres in the solar system. In total, the large efficiency gains of COS will open for the first time a wide window for UV spectroscopy.

Of the two instruments slated for SM-4, WFC3 is the more powerful because of its wide wavelength range and its sensitivity in the near-infrared, which is particularly important for studying the highly redshifted distant universe. WFC3 is thus essential for any servicing mission, while the installation of COS is highly desirable.

FINDING: A minimum scientifically acceptable servicing mission would install batteries, gyros, WFC3, and a FGS. The installation of COS is highly desirable.

FUTURE SCIENCE POTENTIAL RELATIVE TO PAST ACHIEVEMENTS

Hubble's oversubscription factor of about 7 indicates that scientific productivity with the present instruments is already high; the new instruments WFC3 and COS will increase the power of the observatory significantly further. In an attempt to quantify this statement, selected objectives from the above list of future science programs have been identified that, in the opinion of the committee, are comparable in importance to the top ten Hubble contributions listed in Table 3.2. The result is five objectives listed in Table 3.4. Allowing for the overwhelming likelihood of important unforeseen discoveries in addition to those listed in Table 3.4, the committee concludes that the promise for future Hubble discoveries following a servicing mission is *comparable to the telescope's promise when first launched*. The programs listed in Table 3.4 are also very well aligned with the list of key problems highlighted by the most recent decadal survey report for Astronomy and astrophysics, *Astronomy and Astrophysics in the New Millennium.*[21]

[21] National Research Council, 2001, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C.

TABLE 3.4 Foreseeable Major Contributions Made Possible with Hubble

Likely Discovery	Hubble Instrument	Importance
Large number of extrasolar planets	ACS	Possibly detecting Earth-like planets and measuring their radii.
The first galaxies	WFC3	Obtaining key data concerning formation of the first stars and black holes.
Evolution of dark energy	WFC3, ACS	Understanding the fundamental nature of dark energy.
The cosmic web	COS	Mapping the total distribution of matter in the universe.
The effects of quasars and stars on galaxies	COS	Understanding how galaxies limit their own growth.

COMPARISON OF HUBBLE WITH OTHER PLANNED FACILITIES

The unique advantage of HST with respect to other astronomical tools is its exquisite angular resolution extending from the ultraviolet to the near-infrared. Observations in the ultraviolet and part of the near-IR are impossible from the ground at any resolution. Even at wavelengths accessible from the ground, HST still has a big advantage for imaging and low-resolution spectroscopy because of its high spatial resolution and dark sky, which more than compensate for its relatively modest mirror size. In contrast, high-resolution spectroscopy requires a lot of light, so that large-aperture ground-based telescopes are often better, but only if the wavelength is visible from the ground and high spatial resolution is not needed. If either of these conditions is not met, multiple-orbit exposures with Hubble have been successful—for example, for the discovery of black holes at galactic centers.

It has been suggested that a new technique, called adaptive optics (AO), may enable ground-based telescopes to achieve and even surpass Hubble's resolution, at lower cost. The AO method corrects for atmospheric blurring by constantly monitoring the bending of light rays by the atmosphere over the telescope. This information is transmitted several hundreds of times a second to a flexible mirror whose surface is deformed in order to "re-aim" the rays to their original trajectories, restoring above-atmosphere image sharpness. AO is quite new and is still in the development phase. The technique works well in the near-IR (around 2 microns), where ground-based telescopes with AO can actually take sharper images than Hubble. However, it becomes *much more difficult at shorter wavelengths* in proportion to the inverse *fifth* power of the wavelength. Thus, an AO system working at 0.5 microns would be approximately 1000 times more difficult (and perhaps approximately 1000 times more costly) than a 2-micron system; an AO system in the ultraviolet is out of the question. AO systems also have inherently *narrow fields of view* compared to Hubble; these fields of view can be enlarged, but not without considerable further work and cost. AO images are inherently *much less stable* than Hubble images because the atmosphere and the quality of the correction are constantly fluctuating; AO therefore does not lend itself to the precision measurements that Hubble makes routinely. Finally, even if ground-based AO telescopes can sometimes approach Hubble in image quality at long wavelengths and over small fields of view, Hubble still has a big edge in *sensitivity* beyond 0.8 microns because of its much darker sky.

To summarize Adaptive optics is currently useful for certain kinds of measurements in small fields of view beyond 1.6 microns wavelength. Field size and quality of atmospheric correction will improve in coming years, but Hubble will still be superior for nearly all applications through its planned lifetime, even in the near-IR. With time, ground-based telescopes will become more competitive, starting with imaging at longer wavelengths and with spectroscopy (which benefits from the light-gathering capacities of large mirrors). However, for all work requiring high spatial resolution, wavelengths below 1 micron will remain the province of space for the foreseeable future. To equip a 3-meter ground-based telescope today with a system approaching Hubble's image quality at 0.8 micron is technically exceedingly difficult and would be much less stable than Hubble; such a system operating at 0.5 microns is not feasible at present. Thus, Hubble will remain the instrument of choice for virtually all high-resolution observations over its wavelength range during its entire lifetime.

FINDING: Ground-based adaptive optics systems will not achieve Hubble's high degree of image stability or angular resolution at visible wavelengths for the foreseeable future.

The satellites GALEX and FUSE have UV capabilities that are different from those of Hubble and therefore are in no sense a replacement for it. GALEX makes low-resolution images but covers a much wider field of view; its main role relative to Hubble is to find interesting objects for detailed Hubble follow-up. FUSE observes in the far UV at wavelengths beyond Hubble's limit. The missions of GALEX and FUSE are relatively short, with GALEX likely ceasing operation in early 2007 and FUSE in 2010. For efficient follow-up of GALEX discoveries, it is desirable that Hubble operate for three years beyond GALEX, implying a mission lifetime out to 2010.

New facilities under construction or consideration that relate to Hubble's capabilities include the James Webb Space Telescope (JWST). JWST will operate mostly at longer wavelengths than Hubble, out to 27 microns, but the two overlap between 0.6 and 2.5 microns; JWST does not operate in the short-wavelength visible or ultraviolet. The launch date of JWST is currently slated for 2011 but could slip to 2013 given the history of missions of comparable difficulty. With image quality comparable to or better than Hubble's beyond 1 micron and mirror diameter 2.5 times larger, a successful JWST will supersede Hubble in the infrared. Nevertheless there are three important reasons for maintaining Hubble in operation through at least 2010: to lessen the gap in time between Hubble and JWST without any high-resolution space imaging, to permit Hubble to carry out observations shortward of 0.6 microns where JWST cannot reach, and to protect against schedule slips and/or failure in the JWST mission, which is planned for distant orbit without any repair options.

SNAP (renamed JDEM) was envisioned as a project of NASA and the Department of Energy. Plans called for a 2-meter mirror with a wide field of view (0.34 sq deg); it will provide somewhat poorer image quality than Hubble. Its stated goal is to find and study distant, highly red-shifted supernovae for the study of dark energy. Its wide-field optical and near-IR imaging could make it attractive for many other programs, as well. However, it is not yet an approved project, and a start for SNAP is not foreseen until 2015-2016. Moreover SNAP is not a substitute for Hubble because its pixels are twice the size of Hubble's, it has no capability for high-resolution spectroscopy, and it does not operate in the UV. Even if SNAP is completed on an optimistic schedule, Hubble will be able to return a wealth of information about distant supernovae before SNAP is operational. Indeed, the design of SNAP may benefit significantly from these yet-to-be-made Hubble observations.

To summarize, no telescope currently operating or planned covers the wide range of wavelengths and capabilities offered by Hubble, especially in the ultraviolet. JWST offers exciting capabilities in the near-infrared, but JWST has significant development risk and no plans for on-orbit repair. The committee believes that it makes sense to exploit Hubble's proven capabilities for a further 4-5 year period with one more servicing mission.

COORDINATION WITH OTHER FACILITIES

The last several decades have seen an increasing emphasis on multi-wavelength astronomy, in which a panoply of telescopes operating from gamma-rays to radio wavelengths is brought to bear on an object to paint its total "cosmic portrait." For example, x-rays are uniquely able to show hot gas, active black holes, and gas ejected in supernovae explosions; the UV-through-near-IR is the realm of stars, from hot to cool; the deep infrared reveals young stars forming within dark dust clouds; and the radio shows hydrogen gas and energetic plasma ejected from black holes. Each wavelength has its own story to tell.

Among the best examples of synergistic cooperation between different telescopes are recent results using the Chandra, HST, VLT, Keck, and Spitzer telescopes. The Chandra X-ray Observatory has obtained some of the most sensitive x-ray observations ever made of distant galaxies, in both the northern and southern hemispheres. Ground-based telescopes (Keck and VLT) obtained spectra for redshifts and distances; Hubble surveyed both fields and provided much needed high-resolution imaging. The combined result is the detection of hundreds of active galaxies containing super-massive black holes, the integrated flux of which is now known to make up the x-ray background. In fields where neither Keck nor VLT nor Hubble was able to identify a candidate object, the infrared capabilities of Spitzer were able to identify a quasar of very unusual characteristics. These projects are revolutionizing our understanding of the epoch of galaxy and black hole formation and evolution.

It is important that such measurements be carried out almost simultaneously, because high energy phenomena are highly time variable and archival information is not relevant. Most of the x-ray emitters in Chandra deep-field pictures are variable on time scales from days to years. Gamma-ray bursts have even shorter time scales, seconds to days. Much will therefore be lost if the Hubble telescope is not available over the working lifetime of Chandra. Successors to these facilities may not be flown for two decades or more. This argues for continuing the Hubble mission at least through the lifetime of Chandra (5 years from now), and also for servicing early, to maximize the period of simultaneous operations.

Furthermore, the continuation of Hubble surveys, even with the current complement of instruments, is essential to match the requirement of multi-wavelength surveys. Many of the instruments in x-rays, UV, and infrared have wider fields of view than Hubble. This means that Hubble needs to mosaic many exposures to cover the same fields of view as, say, Chandra. Additional time is therefore needed to observe these fields with Hubble, and thus insure a much richer sample of cosmic objects to study.

THE TIMING OF A SERVICING MISSION

A number of strategic considerations indicate that any servicing mission should be flown as early as reasonably possible. Several such considerations are presented above in this chapter, and more are discussed in Chapter 4. They are collected here for convenience.

First, the detector in the workhorse ACS camera is steadily accumulating radiation damage, with significantly degraded performance expected around 2010. Second, gyro failure is expected to place the telescope in one-gyro mode near fall 2007 (see Chapter 4), at which point efficient science operations cannot presently be guaranteed. An interruption in operation will ensue, with the telescope sitting idle on orbit waiting for repair. Such a gap interrupts the normal flow of planning, observation, and analysis, and valuable overlap time with SIRTF and Chandra would also be reduced. Third, battery failure is the one event that can irreparably damage the telescope structure by allowing it to get too cold. This is not predicted to occur until mid 2011 (Chapter 4), but the battery model has considerable uncertainty, and the decline could happen sooner than that. Fourth, the failure model for the avionics (Chapter 4) predicts an increasing number of component failures with time. A robotic servicing mission lacks the flexibility to deal with these. A shuttle mission has the required flexibility but might not have the *capacity* to deal with the added number of problems that a servicing delay might cause. Finally, it is a fact that all predictions for spacecraft longevity are just that, predictions. Components might start degrading sooner than expected, or the telescope could be hit by space debris, or some other unexpected event might occur. For all these reasons, it is prudent to get the maximum science out of the telescope in the shortest time possible, which points to servicing as soon as can reasonably be managed.

FINDING: Servicing Hubble expeditiously is highly desirable.

REHOSTING

A number of studies are underway to study the possibility of rehosting WFC3 and/or COS on a new spacecraft(s). The studies range from a full Hubble replacement, including a lighter mirror but with the same aperture and diffractive limited performance in the UV and optical domain, to smaller single-purpose spacecraft to carry one or the other of these two instruments. There was not time to explore the various possible options thoroughly, and most of them are still undefined in any case. The conclusions here are therefore very general.

It is possible that these studies, when completed, may result in a mission design that essentially replaces Hubble with a new spacecraft and a new mirror of equal performance to be launched as a replacement. The committee notes, however, that this would require a mirror that is at least 2.4 m in diameter with diffraction-limited performance down to the ultraviolet, along with a very accurate pointing and guiding system consistent with HST's capabilities. If all this could be done at a cost competitive to a servicing mission, still taking into account provisions for Hubble reentry, it would be scientifically attractive. However, preliminary cost information provided to the committee suggested that the savings would not be large.

Moreover, all rehost options take time to evaluate, select, and develop, and all options carry the risk that the new spacecraft may ultimately fail to operate to specifications. By contrast, Hubble is a proven platform on orbit now, to which several successful servicing missions have already been sent.

FIGURE 3.1 An example of the Hubble Space Telescope's superior resolution compared with that of a standard ground-based telescope: (left) a distant, peculiar interacting galaxy imaged with the Subaru telescope on Mauna Kea; (right) the same object imaged with Hubble. Subaru (8 m) telescope image courtesy of National Astronomical Observatory of Japan; Hubble (2.4 m) image courtesy of STScI/NASA.

FIGURE 3.2 Two Hubble Space Telescope images illustrate the value of observing at different wavelengths. (left) An image obtained at near-infrared wavelengths, which penetrate the dust, reveals hundreds of stars in the region, as well as a large complex of newly forming stars deep within the dusty column itself. (right) An image obtained at visible wavelengths shows a column of obscuring dust and gas in the famous Eagle nebula (M16). The sculpting away of the dust by an intense rain of radiation from nearby hot stars (off image to top) reveals denser globules of gas inside the column that are seen as protuberances on the surface of the cloud. These protuberances are likely sites of star formation.

Each wavelength imaged by Hubble provides unique information about the sources studied. Images courtesy of STScI/NASA.

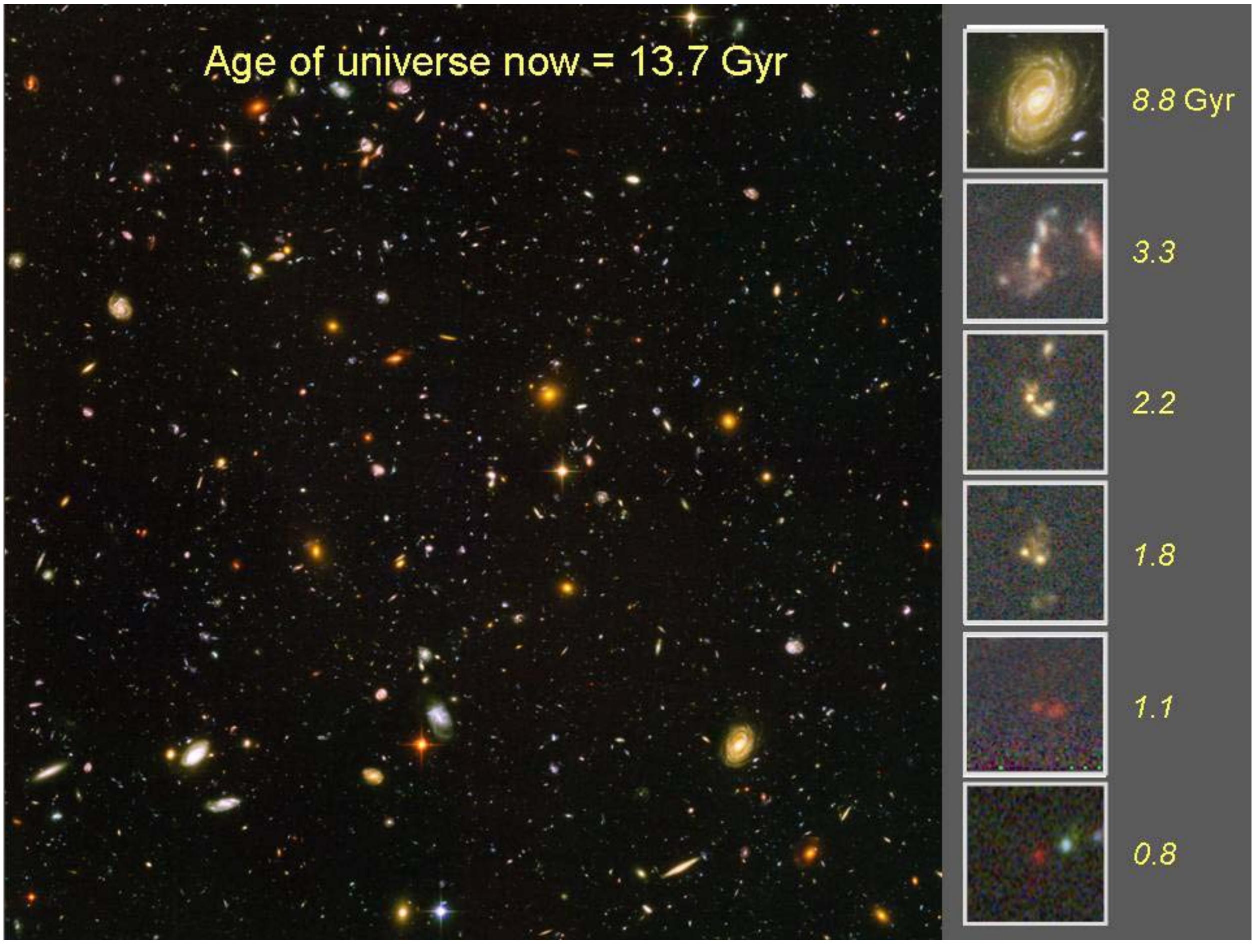

FIGURE 3.3 The Hubble Ultradeep Field, the deepest image of the universe yet taken. Deep images like this one look back in time as well as out in space, revealing the universe as it was billions of years ago. Representative galaxies are shown at the right, along with their ages after the Big Bang (Gyr, 1 billion years). The bottom image in the column is of one of the most distant galaxies yet seen, taking us to within 1 billion years (0.8 Gyr) of the beginning of our universe. Distant galaxies are seen as progressively smaller and dimmer compared with nearby galaxies. Astronomers are using look-back Hubble images like these to chart the course of galaxy evolution. Images courtesy of STScI/NASA.

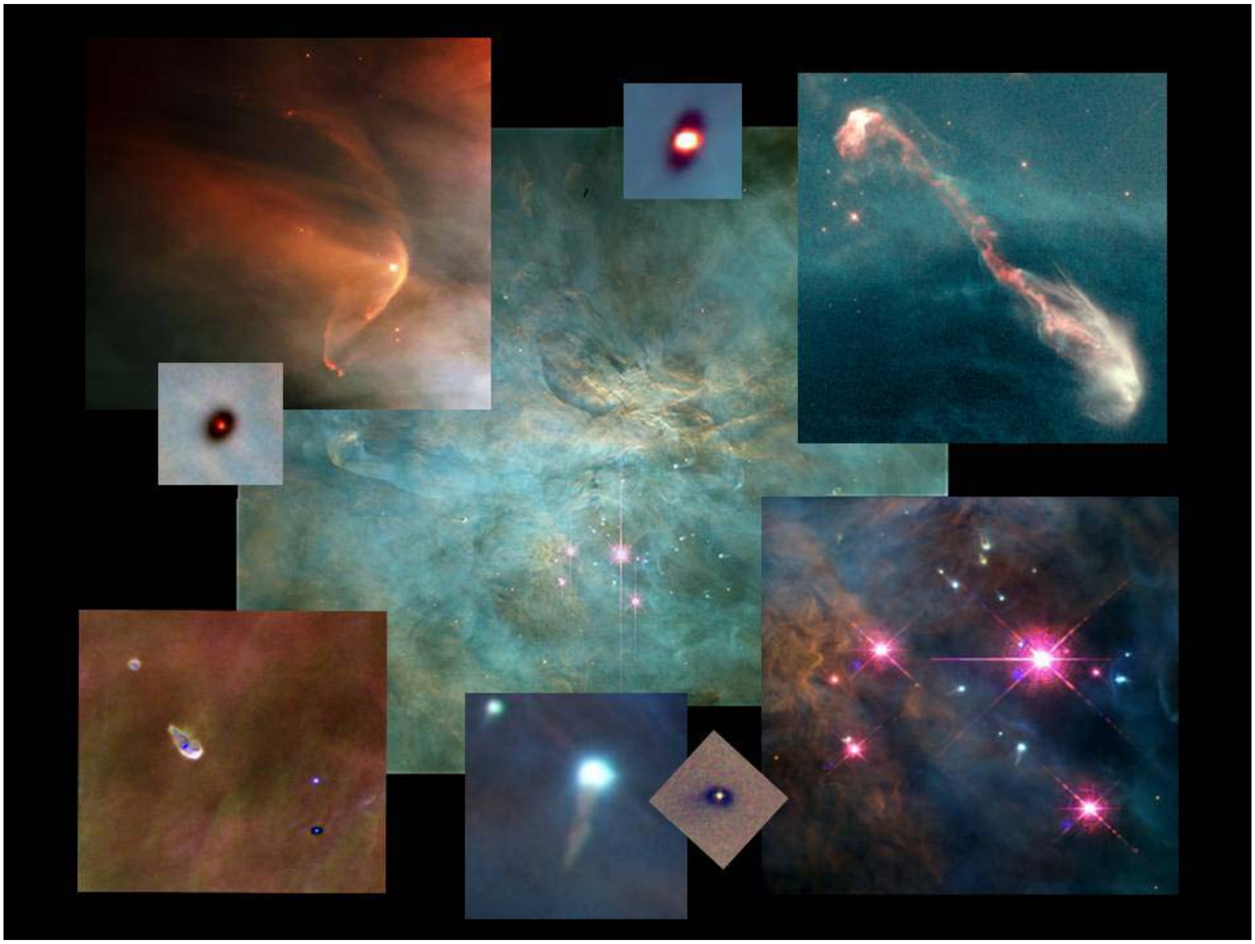

FIGURE 3.4 The Orion nebula, one of the regions of intense star formation nearest to Earth, is a cloud of glowing interstellar gas that has been ionized by the intense ultraviolet radiation coming from five hot, massive stars (the Trapezium) near the center. In this montage of Hubble images, these five very luminous stars can be seen near the center of the main mosaic and in the enlarged image at the bottom left. Energy input from these and other young stars stirs up the gas, giving rise to a network of delicate striations. Despite the chaotic environment, dozens of smaller stars are forming by condensing out of the cloud under their own self-gravity. Some of these stars are surrounded by opaque, dusty disks ("proplyds") that are forming proto-solar systems much like our own. A few young stars are expelling jets of matter perpendicular to their proto-solar system disks (lower right). Fine details of star birth such as these are visible only at the resolution possible within Hubble. Images courtesy of STScI/NASA.

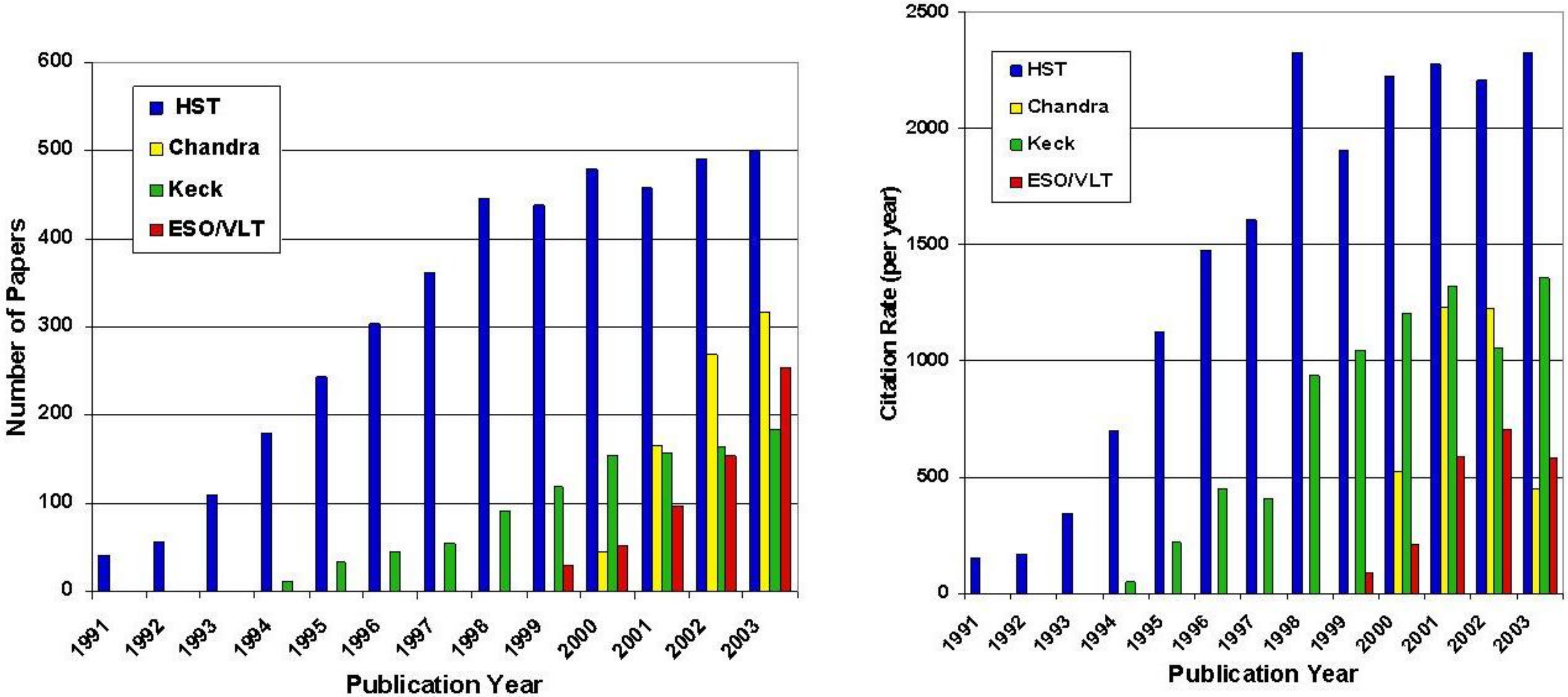

FIGURE 3.5 (left) The number of refereed scientific papers produced annually based on work enabled by major leading telescopes. (right) The number of citations in the scientific literature annually to papers produced from work enabled by major leading telescopes. The criteria used to assign papers to a telescope are parallel for all the telescopes shown here.

FIGURE 3.6 Montage of famous Hubble Space Telescope images. From upper left: (1) Eagle nebula (M16), (2) Lagoon nebula (M8), (3) Cat's Eye planetary nebula, (4) M2-9 planetary nebula, (5) gravitational lens arcs in the Abell 2218 galaxy cluster, (6) colliding galaxies NGC 4038-9 (the Antennae), (7) Eta Carina, (8) "light-echo" ring around Supernova 1987a in the Large Magellanic Cloud, (9) the Hubble Deep Field, (10) auroras on Saturn, (11) Mars, and (12) the black-hole galaxy NGC 4261. Images courtesy of STScI/NASA.

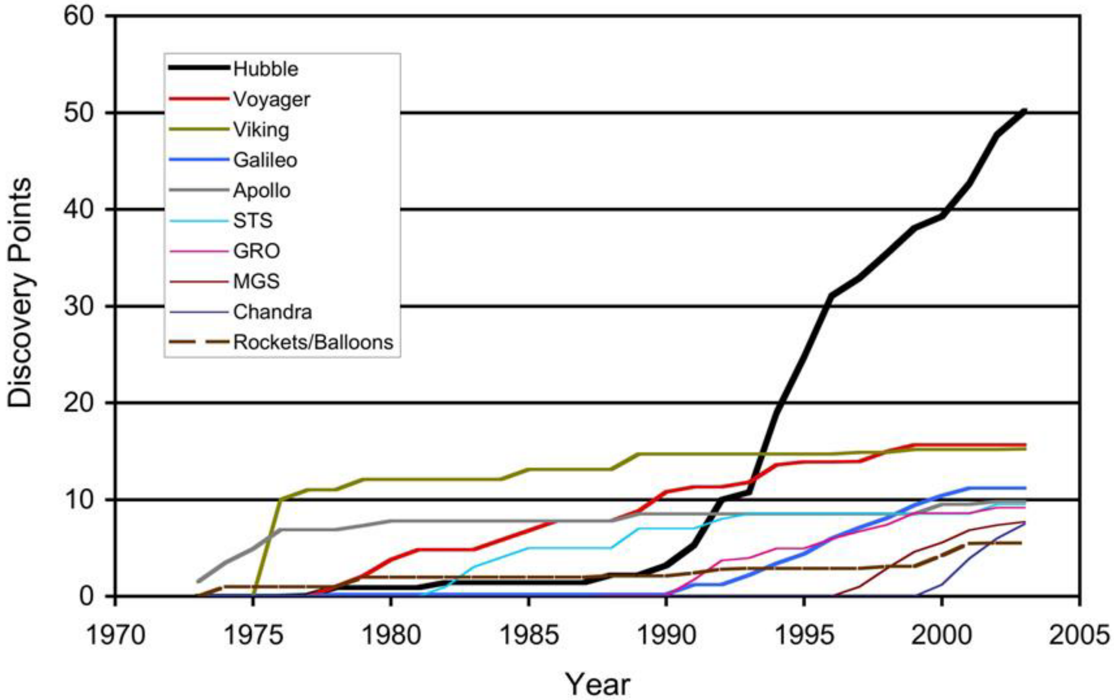

FIGURE 3.7 The cumulative impact of various NASA space science programs as indicated by media coverage. “Discovery points” reflect the number and importance of news stories appearing annually in “Science News.” Courtesy of STScI/NASA.

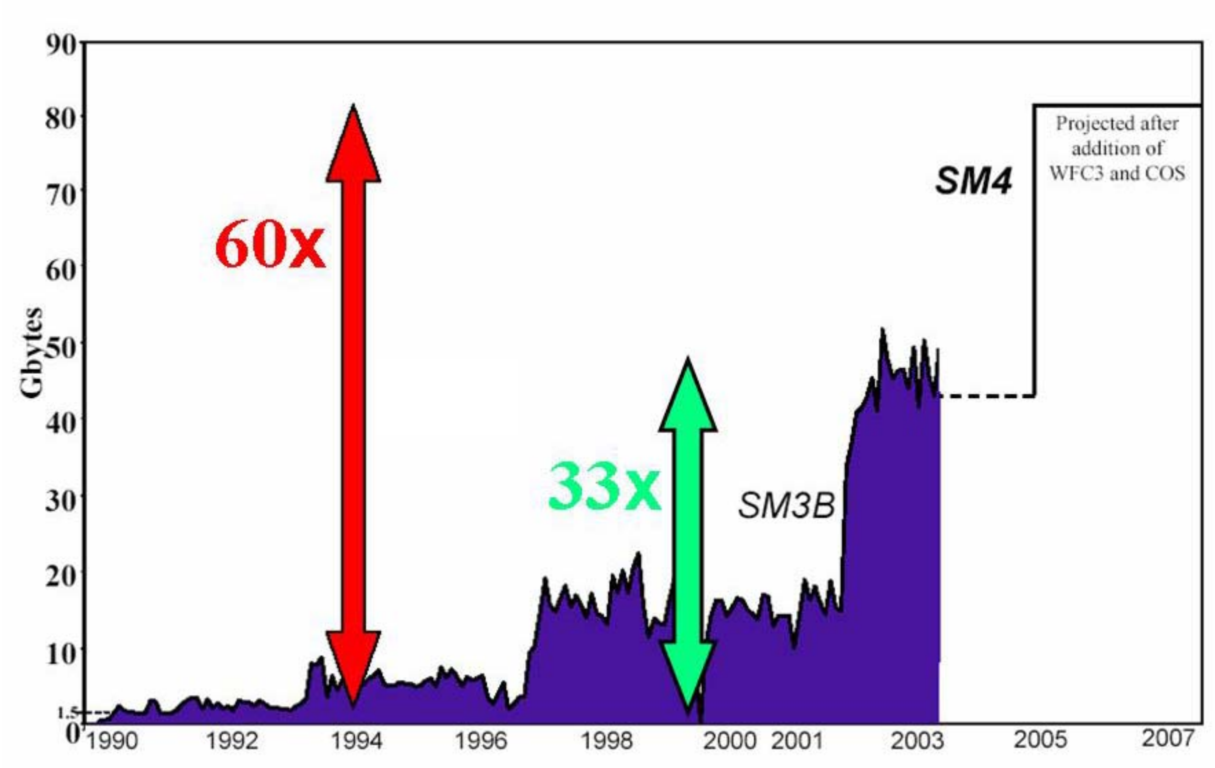

FIGURE 3.8 Growth as a function of time in the volume of data returned by the Hubble Space Telescope, 1990 to 2003, based on the rate of return just after launch. The rate tends to jump after each servicing mission (SM), due mainly to the installation of larger and more efficient detectors. Shown at the right is the volume of data projected as a result of the addition of two new instruments, the Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS) in a fifth servicing mission, SM-4.

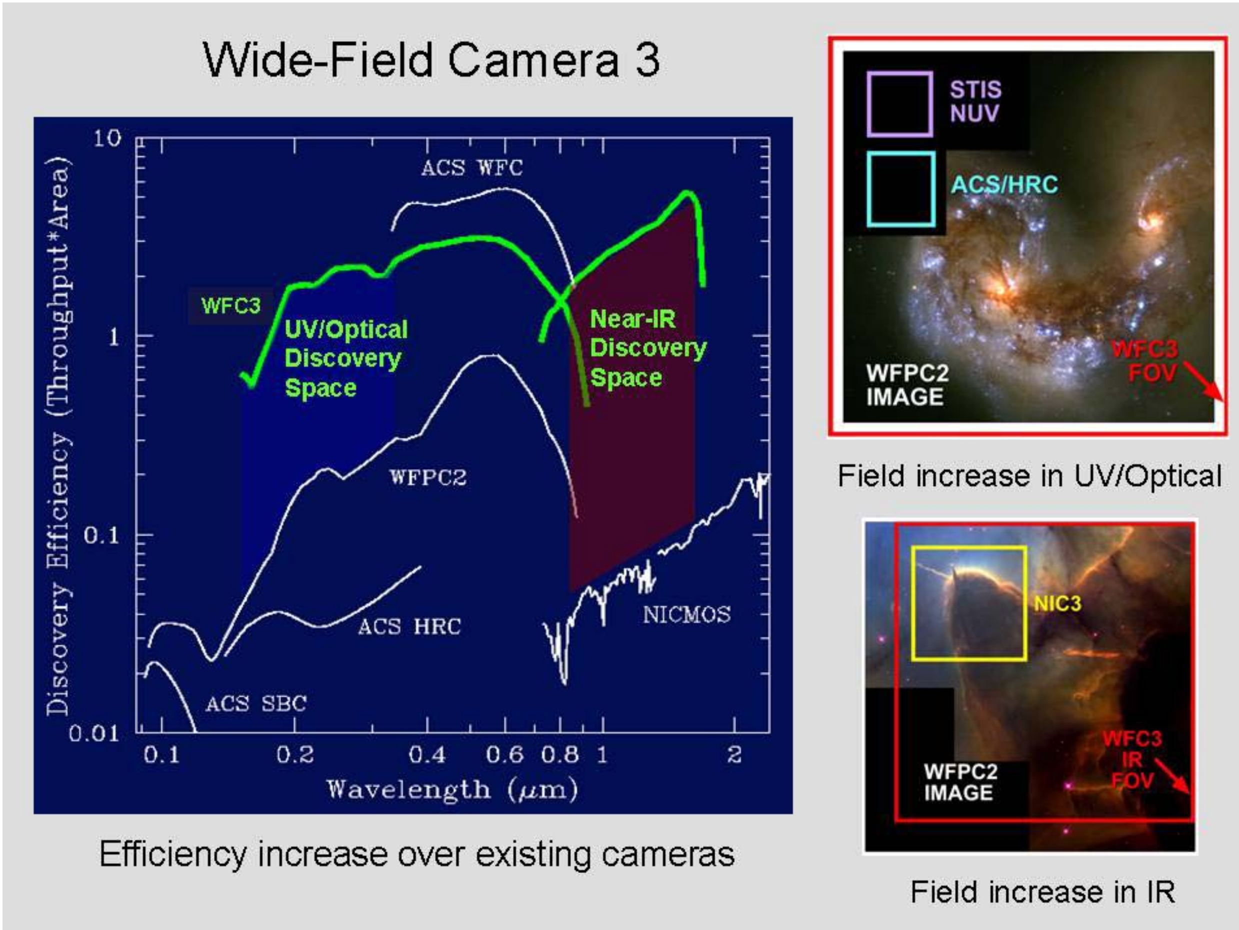

FIGURE 3.9 (left) Anticipated increase in Hubble's imaging efficiency in the ultraviolet (UV) and near-infrared (IR) with the addition of the Wide Field Camera 3 (WFC3). Curves indicate efficiency (explained in the text) for WFC3 versus other cameras on Hubble as a function of wavelength. Note the large gains in the ultraviolet below 0.3 micron and in the near-infrared beyond 0.6 micron. (right) Anticipated increase in the field of view within the ultraviolet arm of WFC3 and in the near-infrared arm compared with the field of view of existing cameras on Hubble. Courtesy of STScI/NASA.

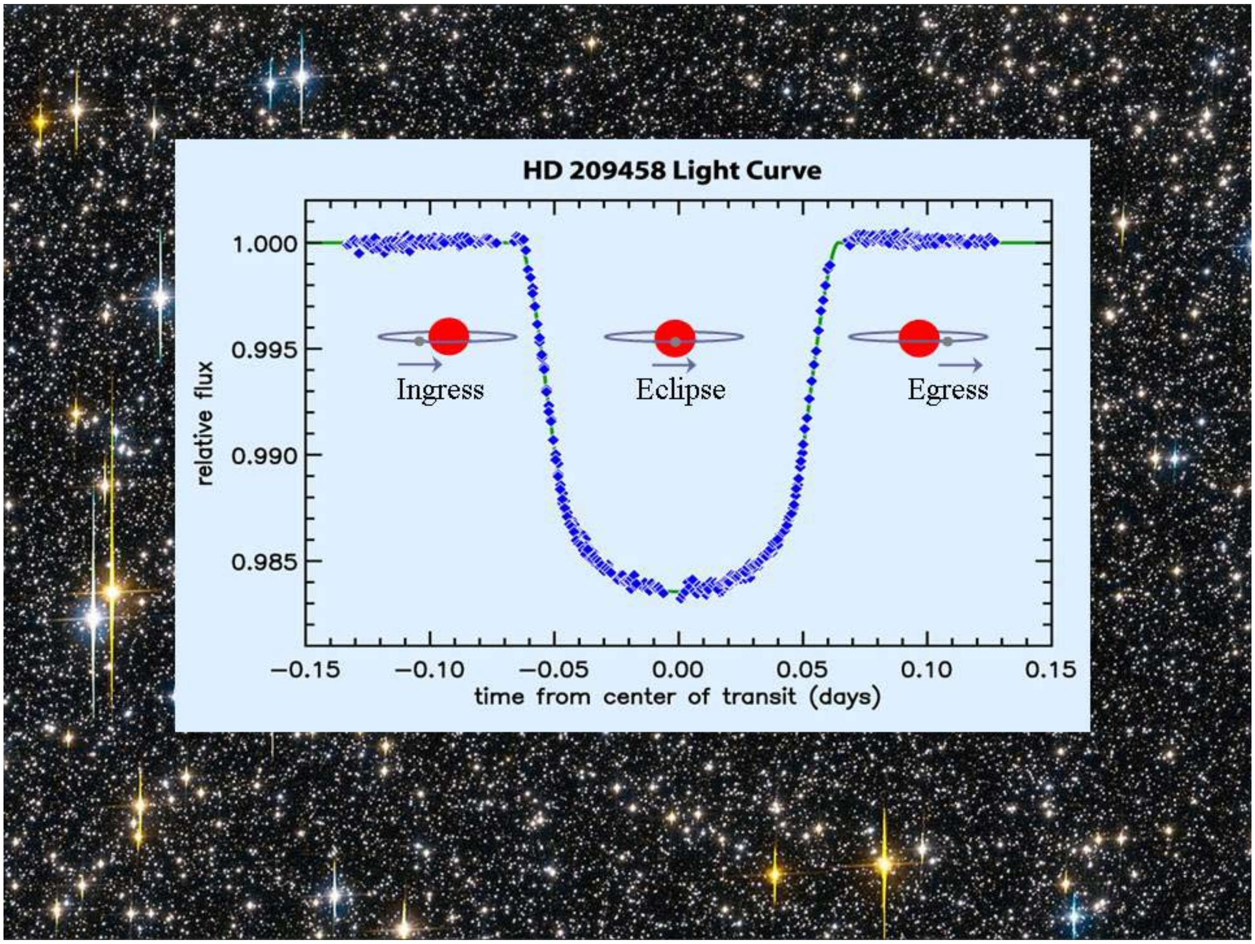

FIGURE 3.10 The presence of an otherwise invisible planet can be detected by the small drop in light caused as the planet travels in front of its parent star. The "light curve" of such a transit is shown here, with the drop in light at slightly more than 1.5 percent, as would occur with a giant Jupiter-like planet passing in front of the Sun. However, the scatter in the Hubble measurements is so small that even smaller planets could be detected. Hubble has begun to monitor rich star fields like that shown in the background, which is a region near the center of the Milky Way Galaxy. In this manner, several hundred thousand stars can be searched for Jupiter-size and smaller planets in roughly 1 week of Hubble Space Telescope observing time. Courtesy of STScI/NASA.

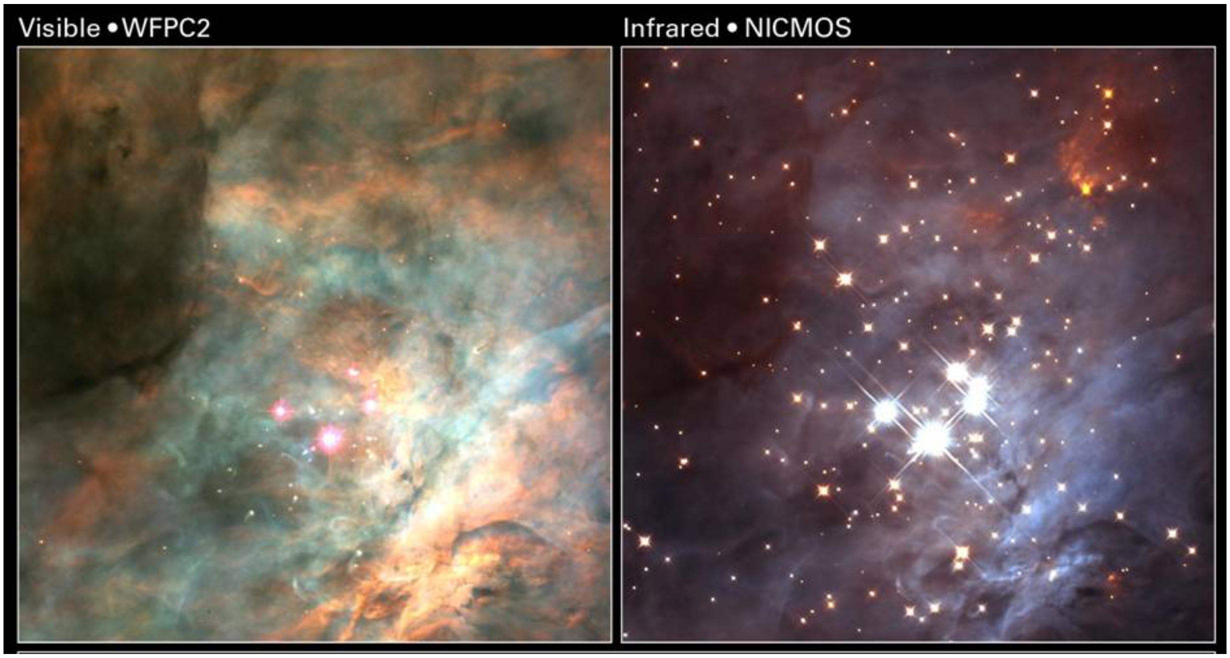

FIGURE 3.11 An illustration of the power of near-infrared light to penetrate dust clouds and reveal embedded, newly formed stars. (left) A Wide Field Planetary Camera 2 (WFPC2) view of the center of the Orion nebula with the five Trapezium stars. (right) The same region imaged in the near-infrared with the NICMOS camera, which makes many previously hidden stars visible. This pair of images illustrates why observing at many different wavelengths is required. Wide Field Camera 3 will be 50 times more efficient than NICMOS for this work. Courtesy of STScI/NASA.

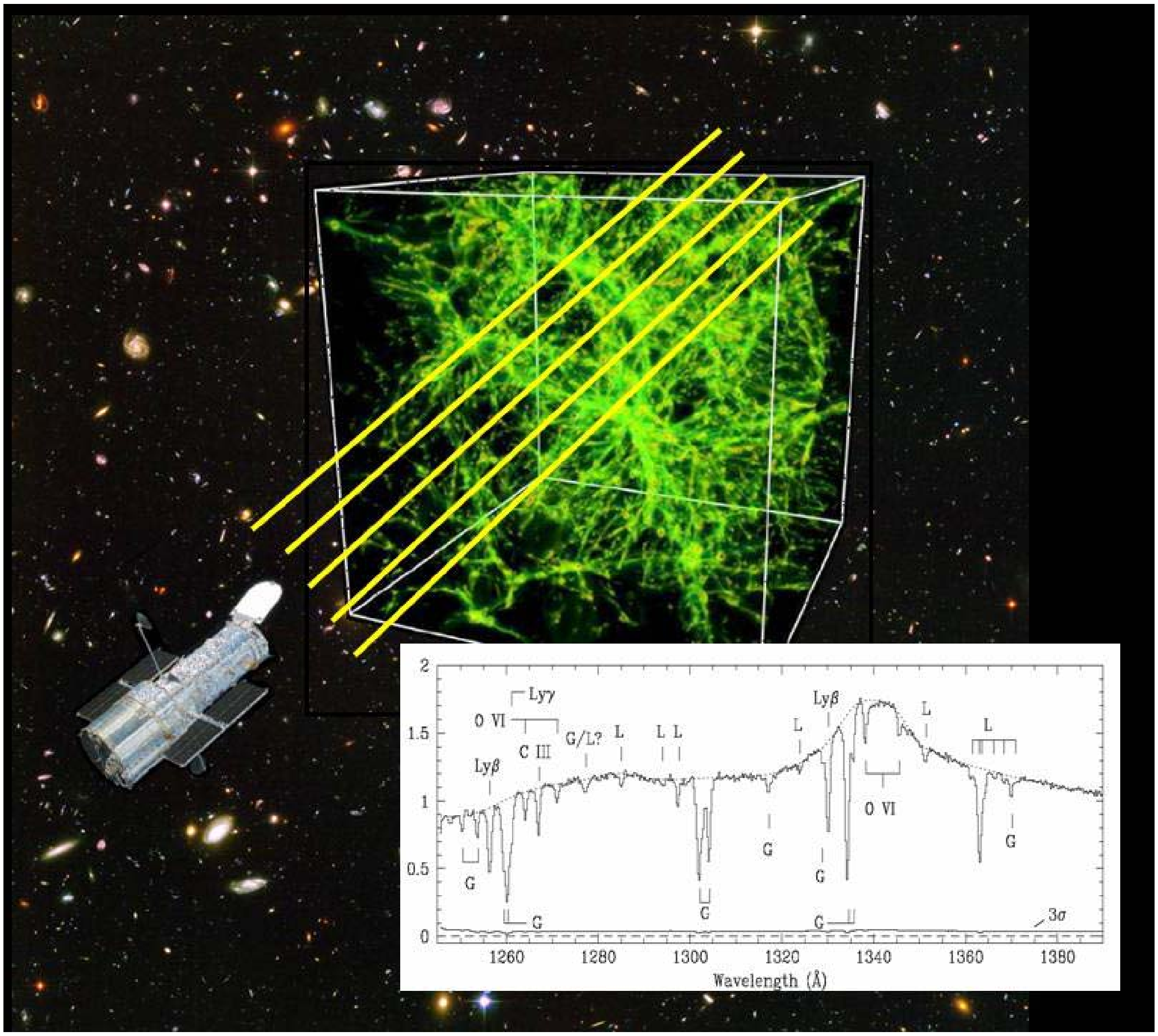

FIGURE 3.12 Theoretical models of galaxy formation predict that the universe is threaded by filaments of matter between the galaxies. It is at the intersection points of this so-called cosmic web that galaxies, and then clusters of galaxies, form. Because it contains only dark matter and gas that has not yet condensed into stars, the web is invisible. However, gas inside it is capable of absorbing light that passes through it on the way to Earth from background objects. Evidence of this absorption can be seen in the spectrum of a background object, which has dips where light is removed by web-gas atoms. A sample spectrum is shown at the lower right. The much higher efficiency of the Cosmic Origins Spectrograph would enable it to take spectra of many more background quasars, creating a dense network of sight lines with which to probe the cosmic web.

4
HST Observatory Assessment and Lifetime Projection

FAILURE MODELING

This chapter discusses the current status of the HST and prospects for its future operations under various servicing options. Essential to this discussion is a model for the failure rate of the observatory avionics subsystems. This model has been developed by NASA and serves two purposes. First, it establishes a time window for servicing the vehicle since inevitable failures (both foreseen and unforeseen) combined with a delay of servicing will ultimately result in loss of the capability to support science. The result is a science interruption where the telescope cannot collect science data but remains in a safe state such that repairs will allow for the resumption of operations. In the event of an extended delay, the risk of accumulated failures can become serious enough to make vehicle survival questionable.

The failure model is also needed to assist in predicting whether a proposed servicing approach can be successful. "Success" here means that the planned repairs, if successfully accomplished, will enable the spacecraft to operate with reasonable probability of success over the *full* post-servicing operating period. NASA has specified this period to be 3-5 years although it will be shown that a timely and comprehensive servicing strategy can improve the probability of success and also potentially extend the post-servicing lifetime.

Failure Categories

This assessment of the HST lifetime divides spacecraft components into three conceptually different categories. The first category contains the science instruments but, since this section is concerned solely with the viability of *spacecraft infrastructure*, this category is set aside. The second category consists of three unique subsystems that are subject to predictable "wear-out," meaning their performance degrades gradually over time in predictable ways that allow for planned replacement. The three key subsystems in this category are the fine-guidance sensor (FGS) units, the rate sensor unit (RSU, commonly referred to as "gyro" or "gyros"), and the batteries.

The third category contains all other components, which the committee terms the "avionics system." The failure model adopted for this last category is crucial, and some of its consequences are counter-intuitive, as explained below. The model assumes that components in this class exhibit random, unpredictable failures *at a rate that is constant over time*. Consequently, the avionics components do not wear out in the traditional sense; if a component lasts, say, 3 years, it is just as likely at the end of that time to keep working as it is today. Eventually, the avionics system *will* enter a wear-out stage, but the failure statistics for electronics parts combined with the performance of Hubble (and other spacecraft) indicate that that the timeframe is beyond the servicing window currently under consideration.

Above, the committee used the words "foreseen" and "unforeseen" to describe failures. Foreseen failures are the predictable failures that affect the wear-out components. Unforeseen failures are the random failures that affect the avionics system. The model for observatory lifetime computes the failure rate of the two categories separately to derive the projected lifetime of the system as a whole.

Previous shuttle servicing missions to HST have demonstrated that essentially all failures on HST are repairable. However, battery failure has unique consequences, since sufficient power must be available to prevent loss of temperature regulation in the optical system. In the case of a severely degraded or failed battery, the temperature to drop below safe limits such that the structural elements of the telescope lose their proper shape. Recovery from this state is not possible.

The HST avionics system is currently fully operable and retains redundancy on all subsystems. (Redundancy is a vital element of spacecraft health; as soon as failures render a key system non-redundant, the projected lifetime becomes much shorter.) The observatory's good condition is the result of extensive efforts since launch by a dedicated and skilled team of scientists and engineers at the Space Telescope Science Institute (STScI) and Goddard Space Flight Center (GSFC). The vehicle is actively monitored on a daily basis and is conservatively operated with the objective of maximizing its performance and lifetime. The avionics system performance has also been extensively modeled and trended using flight telemetry data such that it is possible to credibly forecast system performance, failure trends and replacement requirements.

FINDING: The HST avionics system is currently in a fully operable state and retains redundancy on all subsystems. Its performance is monitored regularly and is well understood by the operations team where it is possible to credibly forecast system performance, failure trends, and replacement requirements.

Repair Types

Failure (both foreseen and unforeseen) rates are sufficiently high on HST that the spacecraft cannot function for an extended period without servicing. Servicing has been done in the past with manned shuttle missions that have enabled three types of repairs. Some repairs replaced components that are subject to *foreseen wear out,* such as the FGS units, gyros and batteries. This class of repairs can be planned years in advance.

The second category, *unforeseen failures* (in the avionics systems and science instruments), such as the S-Band Single Access Transmitter (SSAT) and reaction wheel assembly (RWA), are of a random or unpredictable type that cannot be planned for in advance. Repairs in response to failures in this category must be responded to at the time of occurrence and, historically, have been inserted as late as 3 months prior to a planned servicing mission. In the case of SM-3A, the mission itself (although other servicing work was also performed) was based on responding to an unexpected premature failure of gyros that resulted in an interruption of science operations.

The third category is not related to a failure per se, and should more appropriately be described as a *proactive upgrade* where the intent is to improve system performance or to respond to a long-term downward trend on the vehicle. The Solid-State Recorder (SSR) installation on SM-2 and the advanced computer installation on SM-3A are of this type as are the FGS-2R (projected early failure), New Outer Blanket Layer (NOBL; thermal trend), ASCS (thermal trend), and DSC (avionics reliability) equipment installations that were planned for SM-4.

The difference between foreseen repairs, unforeseen repairs and proactive upgrades leads to two important findings. First, the operational longevity of HST has resulted from both planned servicing activities and the ability to accomplish repairs of unpredicted and unpredictable failures. The ability of manned missions to make such repairs has been crucial to the long-term operability of HST. Second, the reliability, performance, and longevity of the telescope have been substantially enhanced through the implementation of proactive upgrades during past servicing missions.

Since the robotic approach to servicing is new and untried, simplicity will be essential if successful servicing is to be achieved with acceptable mission risk. One key risk consideration is the need to protect the vehicle against undue harm during the mission itself. The second key consideration is that the mission be carried out within a servicing time window in which the vehicle remains healthy and has a reasonable probability of meeting the 3 to 5 year post-servicing science mission goal.

The original SM-4 mission involves many components, including batteries, gyros, WFC3, COS, FGS-2R, the Aft Shroud Cooling System (ASCS), NOBL, and the DMU to SI C&DH Cross-Strap (DSC). Of these, the batteries, gyros, WFC3, and COS, and potentially an FGS,[1] are included in NASA's plans

[1] It is understood by this committee that an FGS replacement has recently been added by NASA to the planned robotic mission. As will be discussed later in this section, replacement of FGS-2R is important in assuring

for a robotic servicing mission; the remainder are important *proactive upgrades* of the sort that have been installed on previous missions with the objective of increasing longevity and maintaining high operational efficiency for the observatory. These ancillary upgrades, which are more difficult to implement and add mission risk, have rightly been eliminated by NASA from the robotic mission plans.

FINDING: Previous human servicing missions have successfully carried out unforeseen repairs as well as executing both planned and proactive equipment and scientific upgrades. The current excellent operational status of the observatory is a product of these past efforts.

FINDING: The robotic mission plan presented by NASA accomplishes the minimum mission servicing goals of installing batteries, gyros, and scientific instruments and potentially a fine-guidance sensor, but does not install other important life-extension upgrades that were also planned for SM-4. It is also unclear whether the FGS replacement or unforeseen repairs can be effected on a robotic mission without exceptional mission complexity and associated telescope risk.

AVIONICS RELIABILITY MODEL

The HST program has developed a model to predict overall spacecraft subsystem reliability as a function of time. The reliability predictions are recalculated and updated based upon the system status at the completion of each servicing mission. This has a crucial implication: if full avionics redundancy and functionality have been restored as a result of the servicing, the mission essentially *resets the avionics system reliability back to unity* as a byproduct of the activity. In other words, the avionics system is considered "like new" after successful servicing under the assumption that all known failures have been repaired, including whatever unforeseen failures have occurred since the system was previously serviced. This ability to "reset the avionics failure clock" has been demonstrated on past space shuttle servicing missions but is not likely for a robotic mission due to the complexity and risk considerations discussed above.

The SPATEL model used by NASA to project the avionics system reliability was originally developed by Marshall Space Flight Center and Lockheed Missiles and Space Company. Progressive updates have been performed, with the current model maintained by the Aerospace Corporation.[2] The Aerospace model determines the overall avionics system reliability by accounting for the failure rates of the individual avionics components (electronic boxes) according to a network of series and parallel connections representing the vehicle end-to-end operable configuration, including redundancy. The component-level approach is based on a standard MIL-HDBK-217 methodology[3] where the failure-rate of individual electrical parts are aggregated into a model for an electrical subsystem unit. The result is a constant unit-level failure rate derived from a parts count and individual part failure rates in combination

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successful extended science operations of HST. However, the location of FGS-2R is considered to add considerable complexity to the robotic mission and may also potentially pose a risk to the telescope if the replacement effort is unsuccessful.

[2] Helen Wong, 2002, "Hubble Space Telescope Reliability Assessment, July 2002 Model," Aerospace Report TOR-2003(2154)-2352, Aerospace Corporation, El Segundo, Calif.; Helen Wong, Aerospace Corporation, "'Less Conservative' Hubble Space Telescope Assessment: Current Model and Post-Service Mission Model," presentation for the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope, dated July 28, 2004.

[3] MIL-HDBK-217 (The E versions is currently in use) is a military handbook specifying a standard method for modeling the reliability of systems using parts count and stress factors to determine component and system level failure rates. Developed in the 1950s at the Rome Air Development Center (RADC), is has a long history of use in military systems including spacecraft.

with complexity factors plus stress factors such electrical stress and temperature. These data are combined to develop a mean time to/before failure (MTTF or MTBF) reliability prediction for the unit.[4]

This committee has closely reviewed the Aerospace Corporation model and finds that it accurately represents the vehicle avionics configuration with regard to operational modes and redundancy. It also follows generally accepted aerospace practices where the electronic box failure rates are modified to 60 percent of standard rates, according to the approach described in RADC-TR-85-229.[5] The failure rate of selected avionics system components are further modified beyond the RADC-TR-85-229 baseline using a Bayesian method to account for specific cases where there are a statistically significant number of failure-free operational hours. The overall method employed by the Aerospace model used on HST is an accepted approach for representing aerospace system reliability and is consistent with practices applied to most satellite systems produced by both government and industry. As previously noted, hardware components dominated by wear-out factors such as the batteries, gyros, and FGS units are not included in the avionics system model.[6] Failure rates of these components are discussed separately below.

The reliability values in Figure 4.1 show the output of the avionics model. The prediction is by year with October 2004 established as the starting date. The 50 percent point (at 4.5 years) based on the model is the nominal reliability value NASA has traditionally used as its baseline to set the servicing interval for HST. Therefore, if the avionics system is working as of October 2004 (T_0) the system is projected to have a 50 percent probability of still being operational (and conversely, a 50 percent risk of failing) as of 4.5 years from that date, or May 2009.[7]

FINDING: The HST avionics system reliability model used by NASA projects a 50 percent reliability interval of 4.5 years. Using October 2004 as a starting date, this interval establishes May 2009 as the latest approximate date for vehicle servicing with at least a 50 percent chance for success.

As noted above, the avionics system model represents a constant failure-rate prediction, so that the failure probability "resets to zero" each moment that a failure does not occur. A shuttle mission such as SM-4 is capable of responding to and correcting both foreseen and unforeseen anomalies. If successfully executed, the failure probability will be reset to zero at the time of servicing. The projected post-servicing probability of success can therefore be read directly from the Figure 4.1 values as 0.69 after 3 years and 0.45 after 5 years. This means that 3-5 years of operation can reasonably be expected after an SM-4 type mission with the projected system reliability being above 0.50 for the first 4.5 years.

A robotic mission does not have the same level of flexibility to deal with unforeseen anomalies unless they are unusually simple and occur early enough in the mission development cycle (prior to CDR) to be effectively accommodated. This means that it is unlikely that the avionics system reliability can be reset through robotic servicing, a result with two important mission implications. First, a robotics mission with an implementation schedule of 4 to 6 years (5.4 years is the projected development time derived in chapter 5 based on an independent assessment by the Aerospace Corporation) will be servicing HST at a time where it is already be near or below the 0.50 reliability point.

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[4] The Mean Time to Failure is the average lifetime of a group of identical components, all described by the same failure model.

[5] Herbert Hecht and Myron Hecht, Spacecraft Electronic Reliability Prediction, Rome Air Development Center Report RADC-TR-85-229, December 1985, Air Force Research Laboratory, Rome, N.Y.

[6] Helen Wong, Aerospace Corporation, "Hubble Space Telescope Reliability Assessment," presentation for the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope, dated August 30, 2004.

[7] It should be recognized that the numbers in Figure 4.1, while quantitatively derived in the avionics model, are essentially a qualitative representation of the system reliability since they reflect many design and implementation assumptions. Despite this qualitative nature, the reliability values are useful for comparative purposes and, as noted in the text, are also the traditional method used by NASA for assessment of the HST reliability.

Second, the extended time until servicing makes it likely that the avionics system will have suffered a component failure that is beyond the capability for a robotic mission to repair. Therefore, while a simple robotic servicing mission performed on a reasonable schedule is likely to be successful, servicing limitations also make it likely that the reliability "clock" cannot be reset. This means the projected avionics reliability will continue from its T_0 starting point in October 2004 with a reliability value of 0.41 at the projected time of servicing in February 2010 and subsequent values of 0.18 after 3 years and less than 0.10 at 5 years.

FINDING: The flexibility for repairing unforeseen anomalies has been demonstrated on past shuttle servicing missions. With this flexibility, the avionics system is projected to operate with a reliability value of 0.69 at 3 years and 0.45 at 5 years in support of science operations following a shuttle servicing mission.

FINDING: The baseline robotic mission is judged to have minimal capacity for responding to and repairing unforeseen anomalies. Assuming robotic servicing in February 2009 (based on a 5.4 year "most likely" readiness date), the system reliability is projected to be 0.41 at the time of servicing, 0.18 after 3 years of post-servicing science operations, and less than 0.10 at 5 years.

COMPONENTS SUBJECT TO WEAR-OUT

An overall HST observatory reliability assessment is dependent on the avionics system components described in the preceding model, plus consideration of other key subsystems left out of the model because their reliability is dominated by degradation according to predictable criteria. Components of this type are subject to "wear-out" described by a reliability model based on either measure and understood trends or physics-of-failure (PoF) assumptions.[8] Key components in this category from an observatory perspective are the batteries, gyros, and the fine-guidance sensors, each of which are scheduled for replacement. The reaction wheel assembly (RWA), solar panels, and several other items (discussed in "Other Reliability Considerations" in Chapter 4) are also in this category but have slow enough wear-out trends that they are not projected to require replacement until after the 2012 timeframe unless an unexpected failure occurs.

Battery Assessment

HST uses a direct energy transfer (DET) power system topology where the solar panels are connected (through intermediate equipment) directly to the batteries. The batteries charge during the sunlit portion of the orbit and then discharge to supply power to the observatory when the solar panels are not illuminated. There are six individual batteries in the system with each consisting of 22 series-connected nickel hydrogen cells.[9] The batteries are grouped in two three-battery compartments, but the batteries are operated and charged in pairs.

The energy capacity of each battery at the time of launch in 1990 was greater than 90 amp-hours with a resulting HST battery system capacity of approximately 540 amp-hours. Recent measurements show that the system capacity is now in the range of 300 amp-hours due to a gradual loss of energy storage capability in each battery over time. Replacement of the six batteries is required on either a shuttle or robotic servicing mission in order to assure 3 to 5 years of post-servicing science operations.

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[8] A physics-of-failure (PoF) approach to reliability uses knowledge of design and key material properties for a unit or device in order to provide a quantitative assessment of reliability and prediction of life under actual operating conditions.

[9] Both the individual cells and the batteries were manufactured by EaglePicher Inc., Joplin, Missouri.

Gradual loss of charge capacity in response to charge and discharge cycles is a normal aging effect for batteries and was anticipated for HST. Energy capacity has been continuously monitored and trended since launch. The batteries have also been periodically "reconditioned" which is accomplished by removing a single battery from service and then cycling it through a deep discharge to an essentially discharged state followed by a full recharge. Battery reconditioning, when performed correctly, helps to restore some capacity to aging batteries. By careful monitoring of the amount of energy extracted during the discharge cycle, determination of battery capacity is also possible.

Despite meticulous efforts by NASA, projecting measured trends to future performance has proven especially difficult in the specific case of HST due to the long service life, thermal constraints during charging, and limitations on the reconditioning method. Given the critical dependence of the observatory on battery condition, an expert working group consisting of NASA and industry experts was consulted to review the most recent reconditioning test results in conjunction with the trend data taken since launch. The consensus conclusion,[10] based on both flight trends and relevant ground test results on similar batteries, is that abrupt wear-out factors (pressurization loss and cell short circuits being the most common and important) will not affect battery lifetime until substantially beyond 2010.[11] Therefore, the relatively graceful degradation trend indicated by current data is expected to continue over the next several years with the batteries following a relatively linear loss of capacity over time.

The working group also projected battery life over time based on the trend data. Figure 4.2 summarizes the results. The red segments represent the consensus opinion of the working group for projected battery life versus time. The *pessimistic*, *most likely* and *optimistic* dates for each of the three segments each follow a linear trend indicated by each of the dotted lines starting (off the graph) at the current battery capacity of approximately 300 Amp-hours (A-h). A capacity loss rate of 37.8 A-h per year represents the *most likely* case based on long-term trends and the latest reconditioning test results. Loss rates of 48 A-h and 30 A-h per year correspond to the *pessimistic* and *optimistic* cases based on available data. The relatively large dispersion between these cases is due to the charging constraints and reconditioning limitations discussed above. However, the specified worst-case and best-case rates of decline are considered to reasonably bound the range of battery capacity loss based on the measured flight battery performance.

The three battery segments of Figure 4.2 also correspond to the three key battery capacity levels associated with operational states for the observatory. The 160 A-h on the upper red segment represents the minimum battery capacity required to support science operations. Once the 160 A-h threshold is reached (based on a battery voltage level representing to a specific discharge level), science operations are suspended and the vehicle transitions to a software controlled Level-1 safe-hold state intended to provide maximum protection for the telescope. The 110 A-h capacity described by the middle red segment corresponds to a more risky hardware controlled Level-2 safe-hold state where the vehicle remains in a safe condition but has relatively little power margin to protect itself from a catastrophic failure. The lower red segment at 40 A-h is the limiting capacity level where the safe-hold function has sufficient power to maintain thermal stability on the OTA metering structure. Upon crossing this threshold, the structural deformation resulting from the loss of thermal stability will result in permanently degraded optics.

Summarizing the information in Figure 4.2: April 2008 represents the *most likely* date for reaching the 160 A-h battery capacity limit resulting in the suspension of science operations and transition into a Level 1 Safe-Hold state. Similarly, July 2009 is the *most likely* date for reaching the 110 A-h limit

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[10] Battery Working Group teleconference on September 1, 2004, consisting of H. Leidecker and J.K. Kalinowski (GSFC), and R. Hollandsworth, H. Holterman, and J. Armontrout (Lockheed Martin), and G. Datum (Eagle-Picher Technologies, LLC) and S. Battel, Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope member, NASA GSFC, Greenbelt, Md.

[11] H. Leidecker (GSFC), series of personal communications, August 2004; Zimmerman, A.H., *Life Projection for the Hubble Space Telescope Nickle-Hydrogen Batteries*, Aerospace Report No. ATR-2004(8180)-3, Aerospace Corporation, El Segundo, Calif., March 15, 2004.

for transition to a less protective and more risky Level 2 Safe-Hold condition. Optical failure of the vehicle is most likely to occur in the May 2011 timeframe when the battery capacity reaches the 40 A-h threshold.

FINDING: Battery lifetime trends are consistent with supporting science operations through April 2008 and maintaining the telescope optical system in a highly protected Level-1 safe-hold state until July 2009. Loss of capability to do science due to optical failure is most likely to occur in the May 2011 timeframe but could occur as early as December 2009 based on a worst-case projection.

Rate Sensor Unit (Gyroscope) Assessment

Gyroscopes consisting of a rate sensing unit (RSU) and an associated electronic control unit (ECU) are key components of the HST control system, sensing drift rates that are used by the pointing control system when pointing and slewing the telescope. The gyros also provide active short-timescale pointing control during exposures (control over longer timescales is provided by the fine guidance sensors).

While observatory survival is ultimately dependent on battery capacity, Figure 4.3 shows that the progressive failure of gyros (green segments) will be the most likely cause for suspension of science operations. There are three rate sensor units on the telescope, each containing two gyro sensors numbered G1 through G6. The gyro design uses a floating rotor in a liquid-filled cavity with electrical connections made using very fine copper-silver alloy flex-wires. These wires experience a gradual metallurgical change as a function of run time on the specific gyro rotor. Failure occurs as a result of corrosion and mechanical fracture due to wear-out processes that are physically understood.

Gradual attrition of gyros was anticipated in the HST system design and has been mitigated through a planned replacement strategy. The most recent replacement occurred on SM-3A in 1999, when all three RSUs were replaced. At the time of this report, G3 and G5 have failed, while G1, G2 and G4 are operational. G6 is turned off and held in reserve. Three gyro sensors (located in any of the three RSUs) are required for 3-axis control of the telescope. However, simulations by GSFC and the STScI indicate that a 2-gyro configuration can, in conjunction with other telescope sensors, be used with only a small degradation in imaging performance. Therefore, the HST project is currently developing software and control algorithms aimed at extending the telescope scientific service life via operation on two gyros.

A realistic reliability prediction for each gyro system has been developed by NASA based on both on-orbit failure statistics and determination of root cause. The prediction for a combined RSU and ECU is the product of flex-wire reliability following a Weibull failure distribution and an exponential probability law characterizing the electronics failure rate (in combination with other failure modes). The projected dates, at 50 percent probability, for transition first to 2-gyro operation and then complete suspension of science operations are July 2006 and September 2007 respectively.[12] If a transition to 2-gyro operation is made in the mid-2005 timeframe, overall gyro lifetime can be extended by up to a year with a corresponding extension of science operations until mid- 2008.

Replacement of the six gyros on SM-4 entails exchange of the three RSUs which are co-located in one of the telescope bays (-V3). The associated ECU units are currently working and do not require replacement. For NASA's planned robotics mission, the RSUs are to be installed on the WFC3 instrument. There is a complication, however, in that it is not possible to interface each RSU to its respective ECU located within the telescope. To overcome this problem, NASA plans to also replace ECUs together with new interface electronics that allow the gyro system to send signals to the telescope

[12] H. Leidecker and W. Thomas, "Notes on the Reliability of the HST Gyros," NASA GSFC, September 10, 2001, available online at http://nepp.nasa.gov/index_nasa.cfm/993/; H. Leidecker, "The Probability of Having at Least Three Operating Gyros," NASA GSFC, June 25, 2002; H. Leidecker and J.K. Kalinowski, NASA GSFC, personal communication, August 30, 2004.

avionics system through an unused test port on the 486 advanced computer (the current plan is to rebuild the ECUs together with the communication interface electronics as a common unit). The cable associated with this data link are routed external to the telescope and are connected to the 486 computer in Avionics Bay 1.

FINDING: If HST operations continue as they are, progressive gyroscope failures are likely to terminate observatory science operations around September 2007. Timely transition to a 2-gyro mode after software validation in the first half of 2005 could extend science operations into the mid-2008 timeframe.

FINDING: HST gyro replacement by the shuttle is a straightforward operation that has been accomplished successfully on past servicing missions. Replacement by a robotic mission is more complex, entailing the attachment of multiple RSU and ECU elements plus interface electronics on to the WFC3 instrument. The interface to the spacecraft system is made via an external cable routed to a test interface on the telescope computer.

Fine-Guidance Sensor Assessment

The FGS units (in combination with their electronics subsystems) are used for precision pointing of the observatory. Due to limits on sky coverage, two operating FGS units are usually required to support the HST observing program. From a reliability perspective, this means that three working FGS units are required to assure that two operational units plus a redundant spare is available to support science operations (this is referred to as "two for three" redundancy).

The three FGS units on HST are designated FGS-1R, FGS-2R and FGS-3, where the number designates the mounting position on the telescope and the "R" indicates that the unit has been previously replaced on-orbit. FGS-1R is currently in excellent working condition, while FGS-2R and FGS-3 are each exhibiting wear-out effects in their servo systems that will ultimately make them inoperable. Based on recent test and performance data, FGS-2R is projected to fail sometime between October 2007 and October 2009, while FGS-3 will fail sometime between January 2010 and January 2012.[13]

FGS units were replaced on SM-2 and SM-3A, and FGS-2R was also planned for replacement on SM-4. The degradation in FGS-2R results in target acquisition failures due to a gradual loss of gain in the servo system. The gain loss is believed to be due to radiation damage to light-emitting diode (LED) devices used in the optical encoder. Recent testing indicates that the system gain has declined to a level that is 5 percent above the servo stability limit with projections indicating that FGS-2R will become unusable within 3 to 5 years. Since the LED radiation effects are time-dependent but are not affected by actual operating time, the lifetime of FGS-2R cannot be extended beyond the projected dates.

FGS-3 has been operating since HST was launched in 1990 and is suffering from bearing wear induced by large coarse-track excursions during early mission operations. An extrapolation of key performance data indicates failure will occur in the 2010 to 2012 timeframe if the unit is continuously operated. Unlike the FGS-2R case discussed above, the FGS-3 wear-out is a function of actual operating time in a target acquisition mode. Therefore, limiting the operation of FGS-3 (through the use of FGS-1R in conjunction with FGS-2R) can potentially extend the life of FGS-3 beyond the currently projected 2010 to 2012 point of failure.

Loss of FGS redundancy due to the failure of FGS-2R is a significant mission risk. Mitigation of this risk was planned for SM-4 through the planned replacement of FGS-2R. The robotic mission

[13] "Hubble Space Telescope Flight Systems and Servicing (FS&S) Program FGS Spare Servo Study Report Prepared for LMTO in Support of the FGS 2R On-Orbit HSTAR Anomalies," Goodrich Document No. TE A16-0523, prepared for Lockheed Missiles & Space Company (LMSC), Greenbelt, Md., April 20, 2004; Mike Wenz, Lockheed-Martin Technical Operations, personal communication, September 1, 2004.

originally presented to this committee could not mitigate this risk since the robotic arm was capable of reaching the FGS-3 position but could not reach the FGS-2R position (in technical terms, the WFC3 is located in the –V3 radial bay of the telescope in the 180 degree position whereas the FGS-2R unit is located in the +V3 radial bay in the 0/360 degree position; FGS-3 is located in the +V2 radial bay in the 270 degree position and could be reached by an arm that is configured to replace WFC3). Since FGS-2R is expected to fail *prior* to the projected robotic mission date, its replacement as part of the robotics mission is considered necessary if FGS redundancy is to be retained during post-mission science operations. However, the mission risk and risk to HST for this activity must be carefully evaluated due to the technical complexity of reaching the FGS-2R location on the telescope.

FINDING: FGS-2R is projected to fail in the October 2007 to October 2009 timeframe. Its replacement is important if FGS redundancy is to be retained to support post-servicing science operations. Replacement of FGS-2R is straightforward on a shuttle mission but considered to be high risk for a robotic mission. Therefore, it is possible to retain FGS redundancy by shuttle servicing and potentially is possible via robotic servicing.

FINDING: FGS-3 is projected to fail in the January 2010 to January 2012 timeframe although, its life can potentially be extended through the near-term use of FGS-2R. Failure in this timeframe will not strongly affect post-servicing science operations if FGS-2R is replaced.

OTHER RELIABILITY CONSIDERATIONS

Solar Panel Assessment

The HST uses a pair of articulated solar panels on each side of the telescope to generate power when illuminated by the sun. Power from the solar panels is used to both operate the vehicle systems and to recharge the batteries. New solar panels were installed on the SM-3B mission in 2002 and have performed normally since that time.

Performance of the solar arrays is continuously trended by the operations team in order to track the average loss of power over time. The power loss, due to a combination of accumulated damage from meteoroid and debris impacts, cracking from thermal-cycling and damage to the solar cells from radiation, is decreasing according to an expected trend.

For the SM-4 servicing case, the trend indicates that power generated by the solar panels will be adequate to support post-servicing operations into the 2014 timeframe. The assessment for a robotic mission is a little more complicated because, the remote location of the batteries (in the DM) requires extra equipment and cabling resulting in an added power loss of approximately 200 watts. Despite this complication, careful power management (by turning off selected instruments and duty cycling of non-critical equipment) should also allow for science operations with either mission option until at least 2014.

FINDING: Solar panel performance is running according to expected trends such that sufficient power will be available to support HST science operations until at least 2014 in the case of either shuttle or robotic servicing.

Reaction Wheel Assembly Assessment

The RWA units are used on HST to provide 3-axis (pitch, roll and yaw) control of the telescope as part of a closed-loop pointing control system. During science operations, the principal modes are fine guidance where the vehicle maintained pointed at a celestial target, and slewing where the vehicle is rapidly moved to acquire targets in different areas of the sky. Four RWAs are used to support normal

HST operations although the telescope can be re-programmed operate on three units with little or no loss of science performance. However, the telescope cannot perform science with only two RWAs. Therefore, if the telescope has a failure leaving it with only 3 working RWAs, it will not have redundancy.

RWA replacements were performed on SM-2 in response to a failure and on SM-3B in response to an operational anomaly (unit RWA-1 was replaced in both cases; although not known at the time, the SM-3B replacement was, in retrospect, more precautionary than necessary). In both of these cases, the RWA anomaly occurred late enough to have the RWA added as an emergency replacement. A record of two late replacements in the span of four missions leads to the conclusion that the ability to carry an RWA can substantially protect against an RWA failure and the associated risk of losing RWA (3 for 4) redundancy. While RWA replacement has been demonstrated during shuttle servicing, a robotic replacement capability is not currently planned. Their location of the RWA units (in Bay 6 and Bay 9) may also preclude their replacement with the planned robotics mission.

FINDING: Retention of RWA redundancy is important to maximize the likelihood of 3 to 5 years of post-servicing HST science operations. Replacement of RWA units has been performed successfully in response to an unexpected anomaly on two previous shuttle missions and is also possible, if required, on SM-4. Replacement of an RWA is not part of the planned robotic mission and may not be possible due to the RWA mounting locations on the telescope.

Thermal Assessment

The SM-4 mission included thermal upgrades to the telescope that are not baselined for the planned robotics mission. Most important of these upgrades are installation of the Aft Shroud Cooling System (ASCS) and NOBL. These are new equipment items developed to mitigate a gradual rise in equipment temperatures on the vehicle. While of a proactive nature, eroding temperature margins on several subsystems mean that installation of the ASCS and NOBL are important if science operations are expected to continue, without thermal impacts, beyond approximately 2010.

Radiation Effects Assessment

An analysis of the effects of radiation damage to HST electronic components was performed by Lockheed-Martin for the HST Project and is documented in a 1998 memorandum.[14] The review, while limited in scope, provides reasonable confidence that the avionics subsystems can be expected to operate to beyond 2010 without any major effects. Unpowered redundant units are also considered to be essentially unharmed by radiation in the HST orbit because the self-annealing rates (for 1970 and 1980 device technologies used on HST) for unpowered electronic parts mostly offsets the accumulation of ionizing radiation effects.

There are currently no telemetry trends (except for the previously discussed FGS-3R LED problem) to indicate that operating avionics units are significantly degraded. Therefore, the overall radiation risk is judged to be low for the avionics system plus FGS units until 2010 and medium thereafter. The risk to the science instrument electronics is judged to be low due to their recent replacement. Since a 3 to 5 year post-servicing robotics mission could extend telescope science operations beyond 2014, avionics failures due to radiation effects could become more likely.

[14] Lum, G., Radiation Reliability Assessment of the Hubble Space Telescope Electronics, Lockheed Martin Technical Memo TM12-97, February 28, 1998.

FINDING: Analysis in combination with long-term avionics monitoring predicts that radiation damage should not interfere with science operations through the 2010 timeframe. Adverse radiation effects after 2010 are more likely, with an increasing risk of avionics component failures if science operations are extended until 2014.

HST SYSTEM LIFETIME AND MISSION TIMING CONSIDERATIONS

HST servicing missions have occurred on an interval of 3 to 5 years. This timing is consistent with the reliability model discussed above in "Failure Modeling" and has allowed for proactive repairs and a timely response to unforeseen failures. The result of this servicing strategy is the HST discussed in this report. It is a vehicle that remains fully operational, with optical performance meeting the original design requirements and science utility that has been systematically improved through both instrument and system upgrades.

SM-4, intended by NASA to be the final servicing mission to HST, was designed to change out key instruments as well as to perform replacements and upgrades to several subsystems. NASA was thoughtful in its choices for the components for SM-4 and the timing for the mission where servicing was planned to be performed in the 2005 timeframe. An SM-4 mission in 2005 satisfied all of the key objectives discussed in this report, by maintaining the continuity of science operations while achieving installation of new instruments and also replacing batteries, gyros and other key system components.

Figure 4.3 provides an integrated picture describing the factors controlling HST lifetime discussed above in combination with a projection of the estimated schedule for the SM-4 shuttle mission and the planned NASA robotic mission. A description of each element of the picture is provided below in the context of mission timing and potential mission results. Starting from the top of the picture:

- *Battery Lifetime Evaluation:* The top 3 *red* bars correspond to the battery lifetime projections for 160 A-h termination of science operations, 110 A-h limit for science survival and the 40 A-h threshold for telescope optical failure as discussed above in "Battery Assessment." Key results are:
  - — Battery capacity is not likely to be the limiting factor for the termination of science operations.
  - — The projected timeframe for a shuttle SM-4 mission should allow for uninterrupted science operations and can be completed prior to the of the worst-case 40 A-h science telescope survival date of December 2009.
  - — The planned NASA robotic mission is likely to occur after the expected date for suspension of science operations but is also likely to occur while the vehicle is in a safe recoverable state.
  - — In the worst combined schedule and battery lifetime case, the planned robotic servicing mission will not meet up with the telescope prior to the 40 A-h threshold for telescope optical failure.
- *FGS Lifetime Evaluation:* The *blue* bars correspond to the FGS lifetime projection discussed in "Thermal Assessment" section. Key results are:
  - — Failure of FGS-2R is projected subsequent to the SM-4 mission but was planned to be replaced. Therefore, the SM-4 mission should result in three working FGS units capable of supporting post-servicing science operations.
  - — FGS-2R is likely to fail prior to the planned robotics mission or early in the operational phase following the servicing mission. It can potentially be replaced in the planned robotics mission.
  - — FGS-3 is likely to be near the end of its service life and will fail prior to the three-year goal for science operations following robotic servicing.
  - — Replacement of FGS-3 as part of a robotic servicing mission can potentially assure having two FGS units available for supporting science operations but does not assure redundancy. Only replacement of FGS-2R can assure redundancy for either servicing option.
- *Gyroscope (RSU) Lifetime Evaluation:* The *green* bars correspond to the HST gyroscope lifetime projection discussed in section "Reaction Wheel Assembly Assessment." Key results are:

— The projected end of 2 gyro operations in September 2007 comes after the recommended window for shuttle servicing.
— Based on the projected time for mounting the robotics mission, there will likely be an interruption of science operations of approximately 29 months.

- *Mission Timing Evaluation:* The next line shows the projected time windows for the SM-4 shuttle option (*yellow*) and the NASA planned robotic option (*orange*). The shuttle option projects the expected 7th and 12th mission dates to define the servicing time window. The robotics mission timeline projects February 2010 (5.4 year development cycle) as the most likely date for mission readiness with October 2008 and February 2011 projected as the best and worst case bounds on the estimate.
- *Mission Comparison:* The lower orange and yellow bars represent the expected post-servicing operations timelines based on the projected shuttle and robotic mission dates. Associated with these bars are the associated orange and yellow mission risk values at the bottom of the figure and the horizontal dashed 50% Risk line. The orange values represent the assessed risk for the planned NASA robotics mission and the yellow values represent the assessed risk for the shuttle servicing case with the vertical dashed lines representing the corresponding dates for the robotic and shuttle mission 50% values. As discussed in section "Avionics Reliability Model," the ability to perform unexpected repairs allows the shuttle risk value to be reset. Hence the yellow values are reset as a result of performing the SM-4 mission whereas the orange values associated with the robotic mission are not reset. Key results are:
  — Early servicing afforded by the SM-4 shuttle mission essentially assures 5 years of operations before other reliability factors might affect the need to suspend science operations. The specific avionics system risk factors are shown in purple on the figure below the "post-shuttle science operations bar, where the 50% risk point occurs after approximately 4.5 years of operations.
  — The projected delay in the robotics mission not only results in a likely 29 month interruption of science operations (as depicted by the blue arrow on the figure) but, due to lower system reliability, is also likely to result in a shorter post-servicing operations period. As shown in purple below the bar labeled "post-robotic science operations," the projected telescope risk value is estimated to above 50% (0.59) at the time of servicing and at a value of approximately 0.82 at the 3 year.
  — The projected shuttle scenario results in servicing of HST prior to suspension of science operations due to gyro failure and should achieve at least 4.5 years of post-servicing operations before the system risk value reaches 50%. Therefore, the total expected operational time in the science mode is projected to be at least 6.3 years for a shuttle mission executed in July 2006 and 7.3 years for a shuttle mission executed in July 2007.
  — The projected robotics servicing scenario starts with 3 years of operations prior to gyro failure followed by a 29 month suspension of operations at which time the projected telescope avionics system risk value will be above 50%.
  — Performing a direct comparison between the two servicing options, 6.3 years of SM-4 associated science operations (1.8 years prior servicing followed by 4.5 years of post-servicing operations) is essentially equivalent to 3 years of robotics associated science operations (all accumulated *prior* to servicing). Furthermore, given a risk value of 0.82 for the vehicle 3 years after robotic servicing (for a total of 6 years of science operations), the equivalent service time for robotics servicing will be approximately 9.5 years.

FINDING: The projected termination in mid to late 2007 of science operations due to gyroscope failure and the projected readiness in early 2010 to execute the planned NASA robotic mission result in a projected 29-month interruption of science operations. No interruption of science operations is projected for a realistically scheduled SM-4 shuttle mission.

FINDING: The planned NASA robotic mission is less capable than the previously planned SM-4 mission with respect to its response to unexpected failures and its ability to perform proactive upgrades. Combined with the projected schedule for the two options, the mission risk associated with achieving at least 3 years of successful post-servicing science operations is significantly higher for the robotic option with the respective risk numbers at 3 years being approximately 30 percent for the SM-4 mission and 80 percent for the robotic mission.

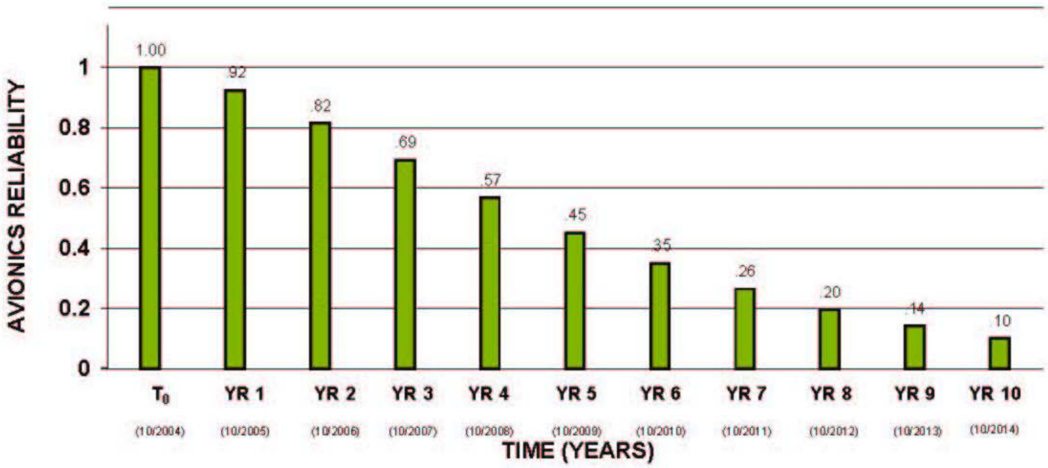
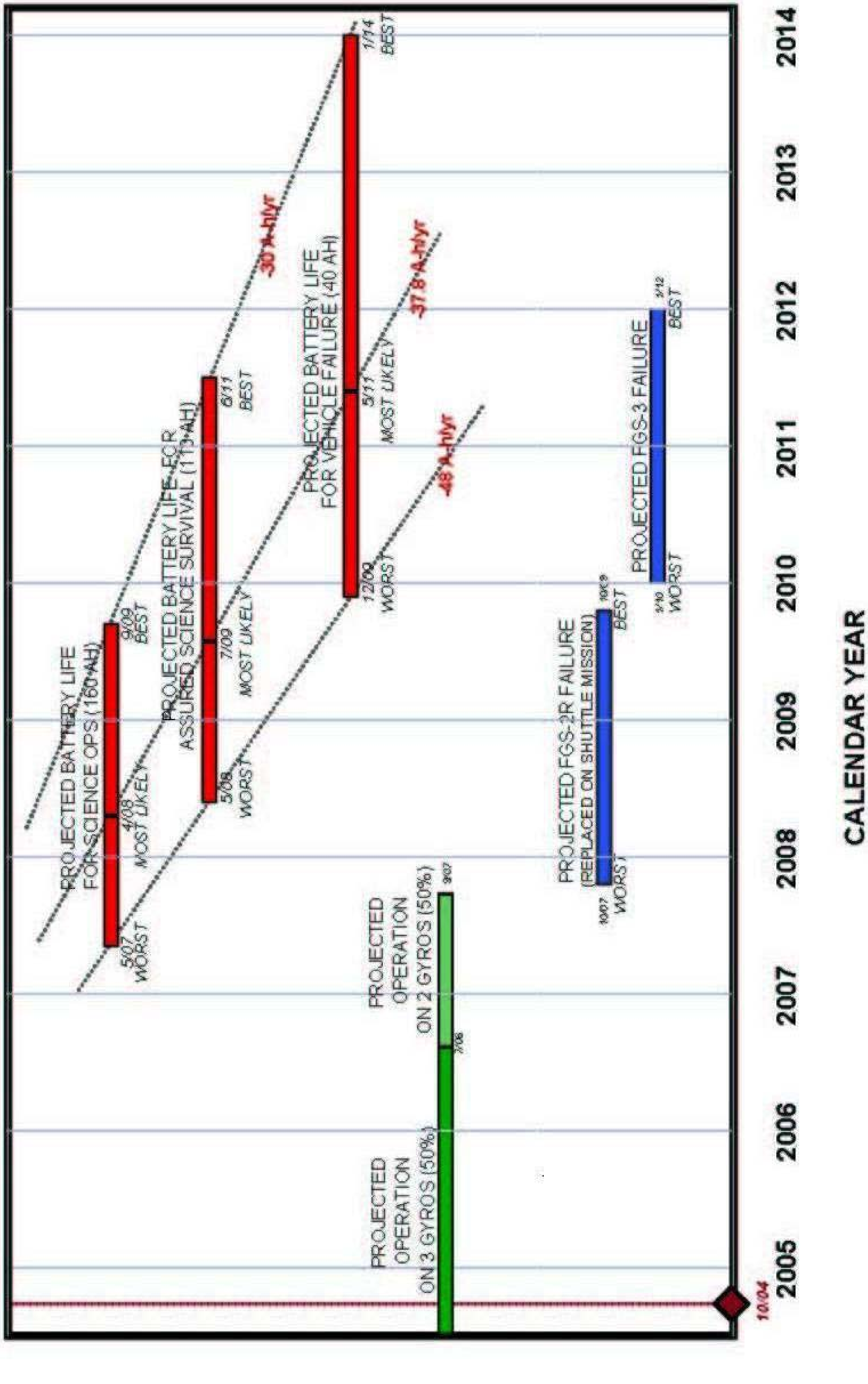
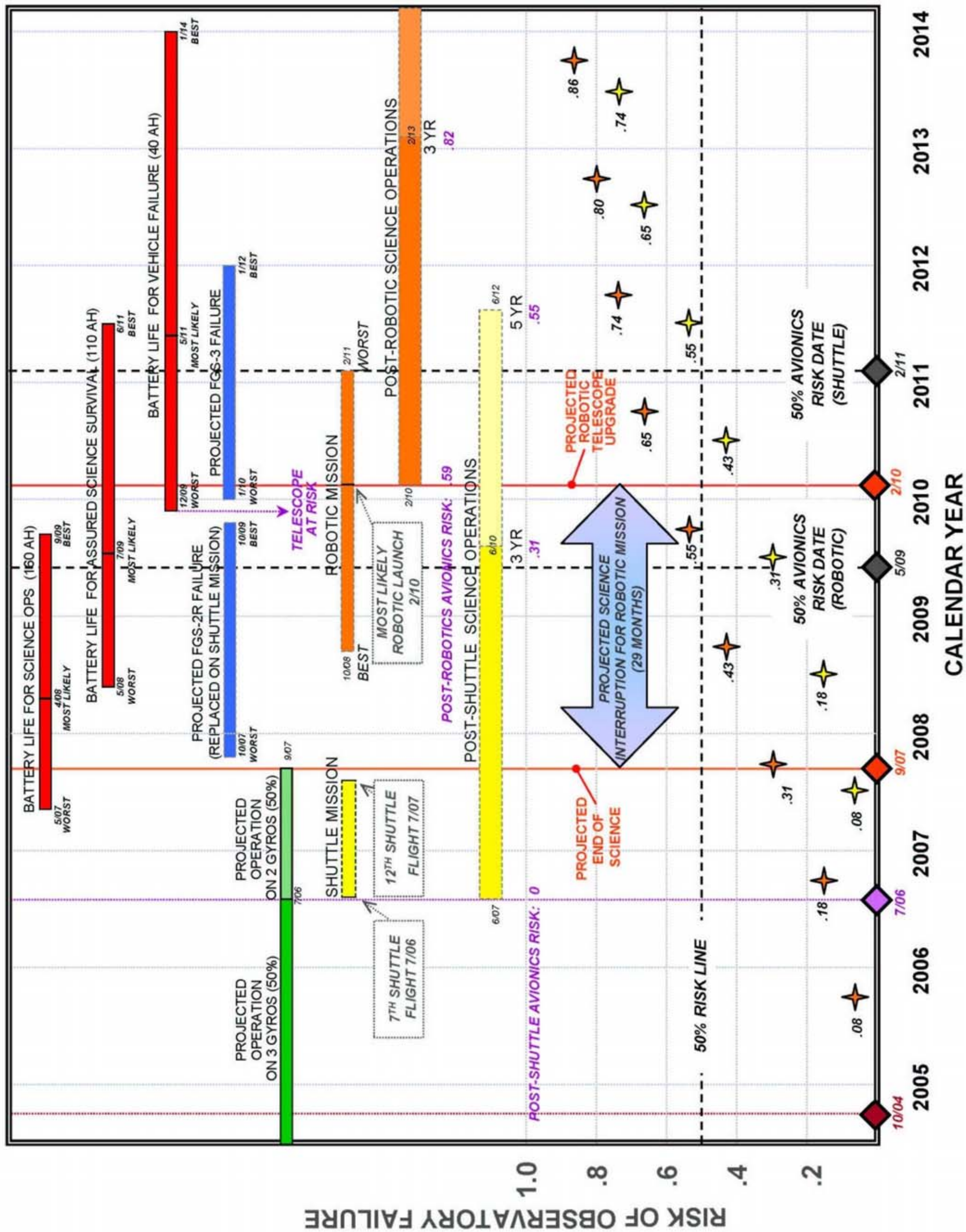


FIGURE 4.1 Hubble Space Telescope avionics system reliability over time. The histogrammed values shown are as of October 2004, at which time the avionics were working and also retained full redundancy. System failure in the context of this figure means that a combination of component failures have occurred (typically failure of both a prime and a redundant subsystem) such that the HST avionics system is no longer capable of supporting science operations. Due to the nature of the system model, as long as the system continues to operate without failure, the same curves translate forward in time with a starting value of 1.0. The risk values associated with these numbers are calculated as 1 minus the values plotted.



PROJECTED BATTERY LIFE FOR SCIENCE OPS (180 AH)
5/07 WORST
4/08 MOST LIKELY
9/09 BEST
PROJECTED BATTERY LIFE FOR ASSURED SCIENCE SURVIVAL (113 AH)
5/08 WORST
7/09 MOST LIKELY
6/11 BEST
PROJECTED BATTERY LIFE FOR VEHICLE FAILURE (40 AH)
12/09 WORST
5/11 MOST LIKELY
1/14 BEST
30 A-h/yr
37.8 A-h/yr
48 A-h/yr
PROJECTED OPERATION ON 3 GYROS (50%)
PROJECTED OPERATION ON 2 GYROS (50%)
PROJECTED FGS-2R FAILURE (REPLACED ON SHUTTLE MISSION)
WORST
BEST
PROJECTED FGS-3 FAILURE
WORST
BEST
10/04
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
CALENDAR YEAR

FIGURE 4.2 Lifetime projection for key Hubble Space Telescope subsystems subject to wear-out. The red segments represent the range of projections for HST battery life for capacity levels corresponding to operational state transitions. 160 A-h represents the limiting capacity for supporting science operations, and 40 A-h represents the limiting capacity for protecting the telescope optics from permanent failure. The three dotted lines correspond to the range of expected loss of battery capacity, −37.8 A-h per year being the most likely rate of degradation. The bounding trend lines for worst and best performance are −48 A-h per year and −30 A-h per year, respectively. The green segment shows the projected time for operation of the remaining four working gyroscopes on HST, with the dark green segment representing projected operation of three gyros before failures (of two of the remaining four units) force a transition to a two-gyro operational mode. The light green segment represents the time duration for operating on two gyros before the failure of one more unit results in the suspension of science operations. The blue segments represent the worst- and best-case estimates for the point of failure of the fine-guidance sensors FGS-2R and FGS-3, based on current trends. FGS-2R is projected to fail due to radiation damage sometime between October 2007 and October 2009. Failure of FGS-3 is projected to occur sometime between January 2010 and January 2012, although it should be possible to extend its life if FGS-1R and FGS-2R are used instead when possible.



RISK OF OBSERVATORY FAILURE
1.0
.8
.6
.4
.2
CALENDAR YEAR
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
PROJECTED OPERATION ON 3 GYROS (50%)
PROJECTED OPERATION ON 2 GYROS (50%)
7/06
9/07
BATTERY LIFE FOR SCIENCE OPS (160 AH)
5/07 WORST
4/08 MOST LIKELY
9/09 BEST
BATTERY LIFE FOR ASSURED SCIENCE SURVIVAL (110 AH)
5/08 WORST
7/09 MOST LIKELY
6/11 BEST
BATTERY LIFE FOR VEHICLE FAILURE (40 AH)
12/09 WORST
5/11 MOST LIKELY
1/14 BEST
PROJECTED FGS-2R FAILURE (REPLACED ON SHUTTLE MISSION)
10/07 WORST
10/09 BEST
PROJECTED FGS-3 FAILURE
1/10 WORST
1/12 BEST
TELESCOPE AT RISK
SHUTTLE MISSION
7TH SHUTTLE FLIGHT 7/06
12TH SHUTTLE FLIGHT 7/07
ROBOTIC MISSION
10/08 BEST
2/11 WORST
MOST LIKELY ROBOTIC LAUNCH 2/10
POST-ROBOTIC SCIENCE OPERATIONS
2/10
2/13
3 YR
.82
POST-ROBOTICS AVIONICS RISK: .59
POST-SHUTTLE SCIENCE OPERATIONS
6/07
6/10
3 YR
.31
6/12
5 YR
.55
POST-SHUTTLE AVIONICS RISK: 0
PROJECTED END OF SCIENCE
PROJECTED ROBOTIC TELESCOPE UPGRADE
PROJECTED SCIENCE INTERRUPTION FOR ROBOTIC MISSION (29 MONTHS)
50% RISK LINE
50% AVIONICS RISK DATE (ROBOTIC)
50% AVIONICS RISK DATE (SHUTTLE)
10/04
7/06
9/07
5/09
2/10
2/11
.08
.18
.08
.31
.18
.43
.31
.55
.43
.65
.55
.74
.65
.80
.74
.86

FIGURE 4.3 Hubble Space Telescope system lifetime and servicing assessment, a composite summary of key factors that affect the operational status of HST and the timing for servicing. The upper six red, blue, and green segments are identical to those shown in Figure 4.2 and represent, respectively, the projected lifetime of the batteries, the degraded fine-guidance sensor (FGS) units, and the gyroscopes, based on current patterns of usage. The yellow and orange segments represent the potential servicing windows for a shuttle mission and a robotic mission based on analyses in subsequent chapters and the resulting time line for a 3- to 5-year post-servicing period of science operations. The timing for a shuttle servicing mission is based on a realistic estimate of the dates for the 7th and 12th missions after return to flight, assuming a return to flight in mid-2005. The timing for a robotic mission is based on the 5.4-year "most likely" development period using historical data for NASA missions and the very high level of mission complexity. To represent the potential range of mission dates, a 4-year best case (high risk) and 6.4-year worst case (low risk) are also shown, even though these extreme values are considered unlikely. The blue arrow indicates the projected interruption in the flow of data for science that would result from combining the projected end of science operations based on gyro failure and the most likely date for a robotic mission. The bottom section of the diagram also represents the risk of HST's failure based on the timing and the method of servicing. (Risk rather than reliability is used in this case in order to be consistent with subsequent chapters and can be derived from the reliability values discussed in Chapter 4 in the section titled "Avionics Reliability Model" by subtracting the reliability numbers from 1.00). The risk values indicated by orange stars represent the risk to HST of a robotic mission beginning at time zero in October 2004 and progressing forward. The 50 percent risk point for the robotic mission value (orange stars) occurs in May 2009, slightly after the projected servicing window opens, but before the most likely robotic service date. The associated post-robotic science operations are seen to begin with a risk factor (0.59) already above the typical NASA limit of 50 percent, with subsequent risk values of 0.82 at 3 years and 0.89 at 5 years (off the diagram). The yellow-star risk values represent the ability to "reset" the risk (or reliability) clock through the capabilities of a shuttle mission to respond to and repair unexpected anomalies (see Chapters 6 and 7). A shuttle servicing mission is likely to meet a telescope that is in good condition, with risk values in the range of 0.20 to 0.30; such a mission would also be able to "reset" the risk back to zero as a result of the servicing effort. Science operations following shuttle servicing of HST have a risk value of 0.31 at 3 years and 0.55 at 5 years. The 50 percent risk point occurs after approximately 4.5 years of post-shuttle operations.

5
HST Robotic Servicing Assessment

PROGRAM DESCRIPTION

In January 2004, Sean O'Keefe, the NASA Administrator, made the decision not to continue planning to use the Space Shuttle for Service Mission 4 (SM-4) to extend the life of the Hubble Space Telescope (HST). In early March, O'Keefe and the Associate Administrator for Space Sciences directed the Goddard Space Flight Center (GSFC) HST project to investigate the feasibility of extending the life of HST by servicing it robotically. NASA developed a set of "Level 1 Requirements" for this purpose, shown in Box 5.1. These requirements have guided the agency in its evaluation of options for robotically extending the life of HST.

The HST Project Team, which includes the Space Telescope Science Institute, concluded that in order to extend the life of HST, as well as continue its high level of scientific return, on-orbit robotic servicing was needed in order to install a subset of the components originally planned for the Space Shuttle based SM-4. Specifically it was considered necessary to install new spacecraft batteries, gyroscopes, and two new instruments, the Wide Field Camera 3 (WFC3) and the Cosmic Origins Spectrograph (COS).

The HST project solicited inputs from industry on how to perform robotic servicing as well as provide the capability to safely de-orbit the telescope. Based on the responses to this request for information (RFI), the project selected and evaluated key elements of the robotic technology required to change out the batteries, gyroscopes and install the new instruments. The HST project also developed a mission operations concept, defined the system architecture and allocated top-level requirements to the ground system and four major flight elements: the de-orbit module (DM); the ejection module (EM); the grapple arm (GA); and the dexterous robot (DR). The project then initiated sole source actions for the GA and DR and a competitive procurement for the DM and EM.

The baseline HST robotic servicing mission program as presented to the committee by the HST Project has a development schedule of approximately 39 months. The spacecraft and instrument hardware that the project has baselined to be installed by robotic servicing are essentially those items that were developed for SM-4. The baseline HST robotic servicing mission is to launch the DM and EM as a package on an expendable launch vehicle, rendezvous with the HST and perform autonomous proximity and docking operations to mate the two modules to the HST. The GA and DM will be contained in the EM, as will be the replacement spacecraft hardware with the exception of the spacecraft batteries. The DM will contain the deorbit motor and the replacement set of spacecraft batteries. Once the robotic servicing operations have been completed the EM containing the removed spacecraft and instrument hardware will separate from HST and deorbit. At the time of this report, although the HST project has performed the high-level up-front systems engineering to establish the baseline architecture, the detailed systems engineering and analysis to understand and define how these elements and the ground system will all operate together as a system remains to be accomplished.

The committee assessed both the program and technical plans as presented by the project as well as an assessment of the readiness of the technology needed to robotically extend the life of HST. The committee's assessment is provided below.

BOX 5.1 Principle Level 1 Requirements for HST

1. Work every feasible operational option and implement where possible, to extend HST's life without servicing.
2. Provide propulsion capability to safely de-orbit HST at some point in the future
3. Do no harm to HST
4. Extend the current scientific program of HST as long as possible
5. Enhance Scientific capabilities with new instruments(s)
6. Provide options to accomplish various levels of the above, which include schedule, risk and cost assessments.

ASSESSMENT OF THE TECHNICAL APPROACH

This section provides an assessment of both the mission-level risks and the technology risks.

Mission Description and Risks

The robotic mission can be broken down into a number of phases that have relatively independent technical challenges and relatively independent risks. This section provides an assessment of the risks associated with the various phases of the mission. It should be noted that 'risks' are discussed in several different sections of this report. In Chapter 7 the different types of risks considered are defined and include health and safety risk, programmatic risk, and mission risk. Of course, technology risks are embedded in the programmatic risks. Mission risks are discussed in this section and qualitatively assessed in Chapter 7. Health and safety risks are discussed in Chapter 6 and programmatic risks are discussed in several places in the report, including Chapter 7. It is important to realize that the risk discussions are abbreviated and qualitative and do not have the benefit of the full-scope risk assessment soon to be completed by NASA.

Pre-Launch Preparation

As summarized above, the DM will be a competitive procurement; the GA, essentially the Shuttle Remote Manipulator System (RMS), and the DR, based on the existing but not yet flown International Space Station (ISS) Special Purpose Dexterous Manipulator System (SPDM), will be procured from a sole source, MD Robotics of Canada. The EM will be built in-house at GSFC. The Hubble Rescue Vehicle (HRV) will thus consist of four major subsystems that will be developed by three separate organizations—GSFC, Lockheed-Martin (recently selected), and MD Robotics. GSFC also will perform the systems level integration and testing in-house and will develop the ground control system based on the RMS and SPDM control station designs, modified to interface with HST hardware.

Risks—There is a major risk in the integration of these different elements into a single payload to be operated by the overall system software, as well as for physical integration of the four elements in the payload fairing and their deployment from the launch vehicle. A very high level of system integration is required because the initial sequence of events, from the launch through the deployment and subsequent stabilization of the spacecraft, is done automatically. Sufficient time and resources will need to be allocated to the program development schedule to integrate and test this payload successfully, especially because it is so difficult to simulate these complex operations on the ground.

There is always the very real risk of a launch vehicle failure, especially in the case of a relatively new launch system such as the Atlas V or the Delta IV. Historical data on U.S. spaceflights suggests that the probability of failure should be estimated at around five percent. Regardless of the launch vehicle, if the failure occurs with the HST payload on board, the entire servicing mission is lost and cannot be attempted again. If the launch vehicle fails (or a serious anomaly occurs) on an earlier mission, there will be a delay of 6 months to 1 year in order to perform the failure analysis and implement the corrective measures. Given the Hubble servicing schedule constraints (see Chapter 4), this could have a major impact on the probability of success of the servicing mission.

Launch

The launch vehicle's ascent performance must be near nominal and the spacecraft must separate cleanly within the allowable tip-off limits. After separation from the launch vehicle, the HRV must rely on its star trackers and the on-board propulsion system to cancel the spacecraft rotation, deploy the solar arrays toward the sun and lock the high-gain communications antenna on the Tracking and Data Relay Satellite.

Risks—Although this is a low and acceptable level of risk, the inability to reach the desired orbit or correctly deploy a functional spacecraft at the desired altitude and orientation will result in the failure of the mission.

Rendezvous

The rendezvous process consists of a sequence of precisely timed thrusting maneuvers that bring the two spacecraft (the HRV and the HST) close together. This requires precise tracking of the relative states of the respective vehicles. Then, coordination and exact timing of the burns of the HRV must be accomplished to assure that the vehicles' orbital planes are appropriately aligned and that the closure rate and angles are precisely controlled. As the distance between the two spacecraft diminishes, the onboard instruments of the HRV (usually star trackers and/or optical cameras) are required to provide precise angular measurements to improve on ground tracking of the target.

Risk—Although the technology is well developed and understood, the short development time presents a risk to being able to fully perform the verification and test required to validate the mission critical systems integration and operations that are unique to the HRV. In some respects, there is no 100 percent effective way to test and verify all these systems operations short of on-orbit testing of the planned HST operational modes, which is not planned. The hardware and software of the Guidance, Navigation and Control (GN&C) systems must integrate across the many subsystems of the spacecraft, including propulsion, sensors, avionics, grapple mechanisms, communication, thermal, and power. This requires a very high fidelity ground simulator to adequately validate all the procedures that may need to be used. Any significant problem that precludes successful rendezvous with the HST will result in failure of the mission.

Proximity Operations

Proximity operations begin when the chasing spacecraft comes into close proximity to the target, acquires the target with a ranging device (radar, camera, or lidar), and settles in on a trajectory to fly in close formation with the target. Once the full relative state estimation has converged and is producing reliable results, the HRV will need to initiate controlled burns to match rates with HST and then move down the capture axis to close in on HST.

Risks—Because of the 2-second communications delay for man-in-the-loop ground control, the HRV must have the onboard capability for autonomous execution when it is in close proximity of HST. In addition, wave-off and abort decisions will be required for mission success under certain predicted failure conditions. These procedures will need to be developed, validated and practiced on the ground. The biggest potential problems concern the inability of the near field sensor suite to acquire HST; any limits on the fine guidance control could preclude the ability of the HRV to fly in close formation with HST and could even result in a collision of the two vehicles. The technologies for near-field sensors and for matching vehicle rates for robotic missions have yet to be demonstrated in flight. Failure to correctly accomplish controlled proximity operations will result in the loss of the mission.

Robotic systems checkout must be accomplished prior to final approach. There is risk at this point that the systems will fail to deploy and/or fail checkout. In such an instance, time for a workaround will be needed before initiating the final approach. It is also possible that the system could fail in such a way that a workaround is not possible, resulting in failure of the mission.

Approach and Capture

This is the phase of flight during which the chasing spacecraft must maneuver to within capture distance and eventually dock with the target spacecraft. During this phase, the navigation system must provide precise relative orientation between the two spacecraft, which as a minimum requires sensors that can provide relative attitude measurements. A series of safe pause points will also be needed to hold relative position, proceed with capture, or terminate the approach. In addition, the spacecraft architecture must accommodate full simultaneous six degree of freedom precise control capability in a manner that avoids plume impingement on the target vehicle (which could make capture impossible or possibly damage HST).

Use of the grapple system to perform the final capture of HST is a significant challenge, and this is one of the key technical aspects of the mission that has never been accomplished in the history of the space program. Some of the required technologies are expected to be demonstrated by an experimental system called the XSS-11 (a DARPA program), but given its timing (late 2006) the opportunity for feedback and incorporation of lessons learned into the HST robotic servicing mission may not occur.

Risks—The capture of HST by the HRV is one of the highest risk portions of the mission. The sequence involves having the two vehicles fly close enough together to enable the GA (which cannot be safely teleoperated, due to the two-second communications delay), to place its end effector over the pin of the HST grapple fixture, engage the snares and stiffen the connection. At some point the control system of HST must be disabled so that the combined vehicle will be under the control of the HRV. The GA then needs to maneuver the HRV down to the aft end of HST and dock it to the HST towel bars, after which the GA can release the grapple fixture pin.

This type of complicated maneuver has never been done autonomously or teleoperated with time delays. It is very difficult to accurately simulate the event on the ground since it involves two vehicles with almost equal inertia vehicles operating in zero gravity. There is some experience in dealing with similar problems on the Space Transportation System (STS), where the shuttle arm has been used to grapple a large payload such as the ISS. But this case has relied on an accurate simulation of the shuttle/arm/station stack and a clear understanding and detailed modeling of the capture envelope of the station/shuttle docking mechanism. The approach and capture of the ISS has been successful because it has the advantage of having astronauts operating directly in the loop (with a better vantage point than will be available from the GA ground telemetry for the HRV) and who are operating with practiced skill and caution, and with no time delay.

When a robotic system is teleoperated with a time delay, such as will be the case for an HST robotic mission system, there is always the risk that the situation will have changed between the last data sample and the time the command is executed. For slowly moving, non-dynamic situations this may be acceptable, but for situations where there is some inherent motion, this could impose a significant mission risk.

The failure of the HRV to successfully grapple or dock with HST will result in loss of the mission.

Robotic System Integration

The execution of the actual servicing tasks can be broken down into a number of challenging but simpler sub-elements. The details of each scenario have not yet been completely defined, but they can be characterized by a set of generic capabilities that are applied to the desired objectives through the use of special purpose tools or end-effectors and careful adjustment of various parameters.

Assuming that the robotic grapple and dexterous systems have been successfully docked to HST using the grapple arm and the rendezvous/proximity sensor suite, the next challenge will be the integration and checkout of the two robotic systems. The grapple arm must de-mate from HST and then grapple the dexterous system, and in so doing must make the necessary electrical and data connections to ensure continuity of command and control. The objective is to optimally operate both robotic systems as one single integrated system. Should that prove to be too challenging in system design and engineering, then the ability to operate the systems independently but harmoniously is required.

Risks—The simple act of decoupling the grapple arm from HST involves two independent risks: the risk of failure to ungrapple and the failure to successfully grapple the dexterous system. The ability to recover from a failure to ungrapple is built into the systems designed for EVA servicing; there is always a method to override the end effectors to release it manually. As with the shuttle RMS, there is also a secondary remotely commanded capability for release using a backup system. It is not clear whether this backup release capability will be present in the HST robotic system design. The likelihood of a failure to successfully grapple the dexterous system at this point in the mission is reduced given the assumed earlier success of the initial capture of HST by the grapple arm. A third risk is that of failure to successfully make all the electrical and data/command connections. Again, such failures during a shuttle mission would be mitigated by manual EVA overrides. A fourth area of risk involves the software development necessary to support the teleoperation or autonomous operations of either or both robotic systems. Historically, complex robotic systems have had difficulty in having sufficient software maturity when flown (as was the case with the first flight of the FTS). In HST servicing the need to successfully integrate the two robotic systems adds complexity and increases the risk and challenge of the mission.

Thermal and Illumination Constraints

The tasks in many of the past servicing missions occasionally were made more challenging because of the limitations imposed on allowable sunlight intrusion on the HST or by the HST thermal environment. While the assumption for robotic servicing is that there will be no such constraints because there are no time limitations for any specific task, consideration nevertheless will have to be given to real-world limitations imposed by HST orientation on each step of each operation. In fact, there may well be some tasks in which timing or thermal issues must be considered.

Risks—Some tasks may be much more difficult if time limitations are imposed. In such an instance, the ability to stop and assess the situation in the event of any particular anomaly will be reduced, and the risk of failure will increase.

Disassembly and Assembly Tasks

The robotic systems will require task-specific end effectors or tools for each step in a given servicing task, including de-mating and mating of connectors. Each assembly or disassembly operation requires the appropriate end effector to be grappled, including the proper positioning and orienting of the end effector, before the part to be manipulated is grasped. This must be followed by the actual assembly or disassembly operation. This operation is particularly complicated in the case of mating and de-mating of connectors. The connector must be grasped, pulled out, docked to a temporary fixture, and then released. At some future point, the same or a different connector will have to be grasped, de-mated from its storage location, manipulated in a carefully controlled fashion, and successfully mated.

Risks—Any time a tool or end-effector is grappled there is a risk of losing the tool and not being able to successfully grasp the tool. There is also a risk that the tool may not work. A further risk is that the tool cannot be successfully released after the operation.

Similarly, when a connector is grasped there is a risk of unsuccessfully de-mating the connector, failing to maintain it with adequate control, bending one or more pins in the connector, and failing to successfully mate it. The ability to successfully de-mate a connector is a direct function of the grip the robotic system has on it. The ability to get into position to get a good grasp and apply the torque in exactly the right direction is a mission risk for every connector. Each scenario will require demonstration preflight using real-world geometry and metrology for every single case.

Bent connector pins have occurred in shuttle servicing missions and have been worked around by utilizing spare jumper cables. There is no reason to think that a robotic system might not encounter bent pins. The ability to recognize that this has occurred will be dependent on the vision system being used (versus the EVA crewmember's direct eyesight). Further, the ability to react to such a case will depend on the spare parts that are carried aboard the robotic servicing spacecraft. Every high priority, mission-critical task using connectors subject to failure will require fallback options for recovery, and the vision system will have to be adequate to detect any such problems when they occur.

Loss of control of a connector/cable could also involve risk, as re-grapple of a free-floating cable (even if tethered at one end) could be a challenge for a robotic system.

Opening/Closing Doors

Some tasks will involve opening and closing access doors. Depending on the case, this opening or closing may be relatively easy or quite difficult. The task for opening the servicing bay doors is a matter of placing a servicing tool on a J-hook bolt, applying the necessary torque for the necessary number of turns, and then actuating the hook to rotate it 90 degrees out of the way. Opening the door is a little more challenging because the door opens outward and away, so the robotic operator will have to pull slowly and carefully and move outboard with the dexterous manipulator simultaneously. More difficulty can occur with the requirement to keep the access doors open to accomplish the servicing task. Shuttle EVA crews tether doors open to keep them out of the way during a servicing task. The plan for this will require development. The axial bay doors are much larger than the servicing bay doors and can therefore be balkier. The particular axial doors that the first shuttle servicing mission crew had difficulty with are not candidates for the robotic mission. However, another set of axial bay doors must be operated in the robotic mission, and there is expected to be considerable challenge in successfully opening and closing them. These doors have several bolts that are accessed with a special interface and the bolts are driven by a standard power tool. There has been some concern in the past about the state of the bolts and the possibility of degradation of the lubricant used on these bolts, but that has not proved to be a significant issue in the past. Again, the doors must be opened outward and away from the centerline, so coordinated movement by the robotic system will be necessary. Also, a tether or door stay of some type will be necessary to keep the doors open and not allow them to drift back into the workspace.

Risks—Inability to open a set of servicing bay doors implies inability to service what lies behind the door, but nothing more. Inability to close the axial bay doors would lead to loss of the telescope's functionality, a much higher risk consideration.

Instrument Change-Out

The details of any particular instrument change-out have not been finalized, but the tasks can be characterized generically. The old instrument must have all connectors de-mated (see above) and moved out of the way, the instrument must be positively controlled, all bolts or other connections holding the instrument in place must be released, and the instrument must be withdrawn and temporarily stowed in a holding fixture of some type. The new instrument must go through the same process to remove it from its stowage location and then install it in HST. Depending on the instrument, one of the most difficult tasks might be determining proper alignment of the new instrument during installation. Taking snapshot data readings of the old instrument upon removal can be helpful in ensuring that the new instrument is properly installed, but this is not an absolute foolproof approach unless the position accuracy of the integrated grapple/dexterous robotic system is kept within very fine tolerance constraints based on allowable misalignment for the respective instrument. These allowable boundary conditions are well understood by the Hubble GSFC personnel for each case. Relying on the data alone is much riskier, however, than having the ability to verify with direct viewing the guide rails and insertion process. Thus the robotic camera pointing, lighting and viewing angles will become critical factors in assuring task success. Force feedback to the teleoperator will be a valuable secondary cue, but it is also not sufficient alone to provide the necessary assurance that no binding has occurred during installation.

Risks—The most significant risks are associated with unintentional misalignment of an instrument and any damage that might result from this. For example, the fine-guidance sensor (a radial bay instrument) has a pickoff mirror at the front end (the center of the pie slice) that is extremely delicate and could easily be damaged by inadvertent contact. Other risks include loss of situational awareness of the extrusion or insertion because of poor lighting or sunlight impact on cameras, poor viewing angles, or unanticipated interference such as sagging multilayer insulation.

Physical Location of the Robotic System

The robotic system will have to be properly oriented so that it can reach all targeted subsystems and instruments for change-out. This simple geometry can be worked out well in advance. However, the integrated robotic system is not able to reach all sides and all elements of HST. This is a particularly important point if it becomes necessary to replace the FGS that is on the side opposite the WFPC camera. In this case, the robotic system would have to move to the other side of HST, which will be an extremely complicated and time-consuming maneuver.

Risks—Failure to properly align the robotic system will alter all task geometries and could lead to an inability to accomplish certain mission objectives.

Redundancy

Each sub-element of each robotic task may require its own unique robotic interface or end-effector. This could lead to dozens, perhaps even hundreds of different tools, each with a unique application. The failure of any one of these tools could have a significant impact on mission success.

Adequate redundancy of functionality will be a major consideration in allocating mission weight and stowage resources.

Risks—Loss of a critical tool or capability could lead to loss of a particular instrument and, in the worst case, could lead to a loss of HST (in the case of the tools used to close the axial bay doors, for example). Similarly, loss of one of the robotic system elements, such as loss of one of the two dexterous robotic arms, for example, or loss of a key television camera, could lead to loss of the mission.

FINDING: The technology required for the proposed HST robotic servicing mission involves a level of complexity, sophistication, and maturity that requires significant development, integration, and demonstration to reach flight readiness and has inherent risks that are inconsistent with the need to service Hubble as soon as possible.

Technology Readiness Assessment

HST was not designed for autonomous rendezvous and docking, and to achieve this through robotic operations presents a number of technology development challenges. The GSFC HST project has done a good job of identifying the technology challenges that have been recognized to date. The project has made an assessment of the technology risks, and these were provided to the committee in the document entitled "Hubble Robotic Servicing and Disposal Mission (HRSDM) Risk Identification for the National Academies of Sciences, July 9, 2004." In the project's analysis, most of the technical readiness levels (TRLs) were given as 8 or 9, with just several lower than TRL level 5.

The committee is concerned about the overall TRLs that the project has estimated for many of the robotic servicing tasks. As discussed above, the Hubble Robotic Servicing and Disposal Mission is a complex robotic mission with a compressed schedule for testing, development, and evaluation. The robotic missions planned by other agencies before or at approximately the same time as the HRSDM will include specific technology demonstrations and evaluations on several aspects of the technology challenges faced in an HST robotic mission, but these demonstrations will provide only limited, if any, opportunity to incorporate lessons learned.

The individual hardware elements (GA, DR, and DM) have been or will be tested on several different missions (STS, ISS, and Orbital Express) but there will be no in-flight experience with an integrated RMS/SPDM system. Similarly, the vision and control software required for the HRSDM will not be tested with the hardware in flight.

The committee concludes that several of the required robotic servicing technologies are at considerably lower TRL levels than estimated by the project, and are also mission critical without a significantly better alternative technology available. For example, relative attitude control during servicing and relative attitude determination fall into this category. There are other technologies, such as the lidar required for near field relative navigation acquisition, although considered by the project to be at TRL level 6, that have not been demonstrated in space. The XSS–11, a USAF mission, is scheduled to demonstrate some technologies such as the lidar and autonomous proximity operations, by March 2005. DARPA's Orbital Express Program, scheduled for flight in 2006, provides a second opportunity to validate some autonomous grappling technology. Because of the time schedule of these demonstrations relative to the HST robotic service planning, it will be difficult to incorporate lessons learned into an HST robotic mission.

The systems level operations, interfaces and software still remain to be designed and tested. The GSFC project has indicated that they are waiting until the prime contractor is selected, and as a result the interfaces and functionality between elements, as well as an overall systems design implementation plan, has not yet been developed in sufficient detail. Therefore, additional schedule and technology challenges are likely to be identified as the next level of design development gets underway.

The committee believes that there are many substantial differences between the proposed robotic HST mission and the previous robotic experience base. Therefore the readiness assessment based on the TRL levels of the proposed hardware is almost certainly misleading.

Critical Technology Readiness

The committee assessed the readiness for critical enabling technology for the rendezvous, capture and robotic operations, as is discussed below.

Rendezvous and Capture

There are very few examples of field-tested operations involving robotic manipulation and assembly with either supervised or non-supervised autonomy, and there are only two examples involving space operations. In 1970, the Soviet Union space program performed rendezvous and capture with a non-cooperative target[1] with a human operator in control and with no communication time delays. (A non-cooperative target is one without transponders or active sensors to provide other space vehicles with its location, identification and/or relative position) In 1998, collaboration between ESA and NASDA produced a moderately successful demonstration using the Japanese Engineering Test Satellite (ETS) VII. This involved a 2-meter-long, six-degree-of-freedom manipulator arm attached to a 2500 kg satellite. Coordinated control of the manipulator and the base was used to minimize reaction forces/moments and disturbances. The ETS VII mission demonstrated autonomous rendezvous and capture of a non-cooperative target. However, in this demonstration,[2] the target was less than 10 cm from the firmly docked position, and it was specially designed for non-cooperative capture. In other words, it was specifically designed for robotic operations and was equipped with fiduciaries for relative positioning and orientation, and included appropriate fixtures for capture.

The proximity operations, autonomous rendezvous and capture, and robotic servicing of the HST requires unique sensors, end-effector capabilities, capture mechanisms and guidance and control algorithms for spacecraft maneuvers relative to a target spacecraft. In particular, Proximity Operations (from approximately 500 m to 3 m) will require the ability to use lidar and/or cameras to control range and bearing. Such a capability has not been flight tested before. In particular, autonomous non-cooperative and non-interactive relative navigation has never been accomplished. Based on the HST Project's assessment provided to the committee relative attitude sensor technology is still at TRL level 3. Finally, the lidar and cameras will have to be used to get to within 3 m of the HST with very near zero relative velocity, requiring the control of all of the relative velocities, including attitude rates. While the committee assesses that this is feasible, it notes that the fact that this has never been flight tested or even accomplished on a similar scale on the ground is reason for concern.

FINDING: Technologies needed for proximity operations and autonomous rendezvous and capture have not been demonstrated in a space environment.

The above procedures will also be required for the attachment of only a de-orbit module to Hubble. This attachment will be required should NASA conclude after the planned mid-2005 Critical Design Review (CDR) assessment that robotic servicing of HST is not a feasible option and that the

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[1] A non-cooperative target is a target that is not equipped with transponders or active sensors, meaning that it cannot respond to electronic interrogation from other spacecraft or emit signals enabling its identification or localization.

[2] K. Yoshida, "Space robot dynamics and control: To orbit, from orbit, and future," in *Robotics Research, The 9th International Symposium,* J. Hollerbach and D. Koditschek (eds.), Springer, Berlin, pp. 449-456.

original shuttle-based servicing mission should be pursued. The risk to attaching a robotic de-orbit module could be significantly reduced if astronauts would install appropriate hardware (such as targets, fiduciaries, and precision latches) at the time of a shuttle servicing. These items would enable the HST to become a cooperative target for the subsequent robotic de-orbit mission. This hardware would provide the best margin of success for docking the de-boost module and for ensuring a more accurate alignment for the center of thrust with the HST center of gravity for the de-orbit rocket firing.

FINDING: The addition of targets and fiduciaries and a better latching system by the astronauts on the SM-4 mission will enhance the ability of the subsequently launched de-orbit module to dock with the HST and provide a more precise alignment for de-orbit.

Control Algorithms and Software

Relative position (via lidar and cameras) will have to be used to grapple and secure HST. Image processing algorithms must accurately detect features (including fiduciaries) from camera/lidar imagery and match these features with a CAD model of HST. The software must be able to use information about the detected features to automatically register the end effector with respect to the features and then control the end effector of the grapple arm to maintain relative positioning with errors less than 10 cm and relative orientation with errors within 1-2 degrees. This level of final position accuracy is critical for successful instrument change-out where clearances can be as small as 1/2 cm. It may be not be feasible to accomplish this on HST because it was not designed for robotic operation and does not have the fiduciaries that a target for robotic capture should have. Further, because of the deterioration of the insulation and of the exterior of HST in general, there could be noticeable differences between the actual HST condition and the CAD model of HST that is used in the software development. Finally there is a risk associated with the docking procedure during which the HRV and HST must be brought closer by the grapple arm so that it can dock to the HST towel bars. The rates of the combined system will have to be regulated by the propulsion system on the HRV and the dynamics of the large HST payload at the end of a long arm will excite low frequency modes in the structure and the control algorithm. Most importantly, while there have been several proof-of-concept demonstrations of autonomy in similar tasks (but on a much smaller scale) in research laboratories, nothing on this size has been demonstrated or tested, on Earth or in space.

It should be noted that some of the technology risk will be alleviated because human operators can be involved in the command and control loop. Autonomous operations can be limited to several seconds of operation at a time, allowing the human operator to monitor the progress of the task and to intervene as necessary. However, the performance of such human-in-the-loop teleoperated control systems will be significantly degraded by the communication time delays of up to two seconds.[3] Extensive testing will be required to reduce the technology risk associated with grappling and securing the HST.

FINDING: The control algorithms and software for lidar and camera based control of the grapple arm are mission-critical technologies that have not been flight-tested.

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[3] Up to a two second time delay results from the multiple roundtrip communications required, between the HST control center and the HST through the Tracking and Data Relay Satellite, for "real-time" commanding, command verification, telemetry confirmation of commanded actions, as well as for any resulting corrective actions needed.

Robotics Operations

The servicing mission includes the installation of batteries, the gyros and the WFC3 package, and the COSTAR/COS change out. This requires opening and closing shroud doors, the manipulation of HST SA3 DBA2 connectors to tap SA3 power feeds to recharge the new batteries, and de-mating and re-mating connectors. All of these tasks will be performed by the dexterous robot (DR) equipped with special purpose tools and end-effectors. The committee concludes that the hardware solutions proposed for the tasks are relatively low risk, that the software and control algorithms for the DR/OEDMS are medium risk and that the vision based closed loop control is high risk.

Again, because human operators can be involved in command and control, autonomous operations can be limited to several seconds of operation at a time, significantly mitigating the level of risk involved. But because of the time delays, the operation of the robotic system will not be like the human-in-the-loop systems that NASA has deployed on the shuttle or the ISS. The force feedback information may be difficult to interpret and react to. In principle, punctuating short, scripted, guarded moves with human monitoring and control at every step, although very tedious, is feasible. However, no systematic tests have been done at the scale envisioned in this mission over an extended timeline of weeks or months. Further, the software architecture requires complex distribution and integration of sensory data processing and control arbitration across computers that are in orbit and on the ground.

FINDING: Technologies needed for autonomous manipulation, disassembly and assembly, and for control of manipulators based on vision and force feedback have not been demonstrated in space.

PROGRAM ASSESSMENT

This section provides the committee's assessment of the Project Technical and Programmatic Management Plan.

Project Team

The Goddard Space Flight Center (GSFC) is responsible for the overall management of the HST program, including normal operations and periodic servicing missions. The GSFC has supported the HST robotic servicing mission by providing resources as needed to the Project Team, composed of Civil Service and contractor personnel with long Hubble experience, augmented by technology experts in the areas of guidance, navigation and robotics. Throughout their interaction with this committee, it was clear to the committee that Project personnel are dedicated to successfully carrying out an HST robotic servicing mission. The committee notes, however, that the Goddard experience base in robotics is limited, with no on-orbit experience, and that the Goddard team has virtually no flight experience with autonomous rendezvous and docking.

Although the situation may change as a result of the NASA administrator's commitment to proceed with the development of the robotic servicing capability, it was not evident during the committee's discussions with the Project Team that the HST Robotic Servicing Project has requested or received the commitment it needs for success. Application of the full breadth of NASA technical expertise is vital to this project, yet the committee has seen no evidence that this support has been provided by either the Johnson Space Center or the Jet Propulsion Laboratory, which are organizations with directly applicable mission operations and robotic technology expertise.

FINDING: The Goddard Space Flight Center HST project has a long history of HST shuttle servicing experience, but little experience with autonomous rendezvous and docking or robotic technology development, or with the operations required for the baseline HST robotic servicing mission.

Program Development Plan

The committee evaluated the state of the HST robotic servicing mission system design, program definition and development plan as provided by the project, as discussed below.

Systems Engineering

Although the GSFC HST project has developed the initial architecture for the top-level systems engineering, the detailed systems engineering, analysis, and requirements flow down to understand and define how the flight elements and the ground system will operate together as a single system remains to be accomplished. A robotic mission of this complexity requires a significant amount of up-front systems engineering and trade studies based on thorough analyses and simulations just to arrive at a starting point for the system design. This level of design definition is normally done before commitment to hardware procurements, especially for a mission as technically complex[4] as the HST Robotic Servicing Mission. Historically, in the experience of the committee members, inadequate upfront systems engineering has been the primary cause of significant program schedule delays and cost overruns. Furthermore, the committee believes that initiating the hardware procurements before completing the system level analysis may lead to an unnecessarily complex mission implementation. Specifically, the present mission approach focuses on de-orbit prematurely and has selected a complex mission design that requires three modules, the de-orbit module (DM), the ejection module (EM), and the robotic module (RM), and four separate procurements, the DM, the EM, the grapple arm and the dexterous robot. Further, GSFC will provide all the as-yet undefined element-to-element and operational interfaces.

The system engineering during the development phase will present a significant challenge because of the complexity of the design approach. As one example, there are a large number of program elements that must be integrated into a single operational system, with an over-arching set of system software that will not be defined until after the element prime contractors have begun their design phases. The committee points out that the present plan to develop the various elements of the robotic program in parallel, in various parts of industry and government, will require a strong, central system engineering and integration function that must be extremely active in its oversight of the program.

NASA management has indicated that the integration will be accomplished in-house at GSFC. The committee is concerned that this approach requires a significant broadening of the GSFC HST project responsibilities beyond their previous experience base. Not only will the project oversee the development of the replacement scientific instruments (already completed) and the development of the necessary tooling and implementation of the on-orbit robotic operations, but the project will also be asked to oversee the development and integration of two major spacecraft modules (the DM and the EM) and two different robotic systems (the GA and the DR). This approach could work if there is assurance that there will be an adequate number of highly experienced and capable personnel assigned to accomplish these demanding tasks. Even in this case, there may be insufficient time to carry every task to a satisfactory completion.

[4] Appendix A provides an overview of the state-of-the-art in robotics technology for the reader not familiar with robotics.

FINDING: The GSFC HST project has accomplished a great amount since January 2004. However, there remain significant technology challenges and major systems engineering and development challenges to successfully extend the lifetime of HST through robotic servicing.

Schedule

The proposed HST robotic servicing mission development schedule of 39 months presents a very difficult challenge in terms of the acquisition and program management strategy. In the briefings presented by the project to the committee it was clear that most of the constituent elements of the mission are well understood by NASA and their supporting industrial partners, with perhaps a few exceptions (such as relative navigation and guidance technology). As individual elements these present no special development problems, provided adequate time is available. However, the schedule allocated for the system level design integration and validation is extremely aggressive and therefore carries high risk.

The committee believes that the technology development and design integration challenges for the HST robotic servicing mission are being seriously underestimated by the project. Given the state of the current system design, for example, it is unrealistic to expect to have a reasonably thorough preliminary design review (PDR) less than 3 months and a critical design review (CDR) 9 months after contract award, as is currently envisioned by the project. This is especially true given that this effort (a) has not had detailed pre-award, system definition studies; (b) requires critical in-line technology developments; (c) involves multiple contractors; and (d) currently has an undefined set of system level operational and software interfaces. Further, because of the lack of maturity of the program plan, the project was unable to identify for the committee a data-based critical path in the schedule, further undermining the credibility of the current schedule.

The Aerospace Corporation's historical database of different space missions of various levels of complexity versus development time is shown in Figure 5.1. The analysis to determine where the HST robotic servicing mission elements fit, as shown in the figure, was developed by the Aerospace Corporation for NASA as part of an assessment of the risks of being able to meet the objectives of the baseline HST robotic servicing mission, and to evaluate any potential reductions in risk that might be offered by less ambitious HST servicing alternatives. Figure 5.1 compares the complexity of the DM, EM, and EM plus RM, each with a baseline development of approximately 39 months, with a large set of other missions contained in the historical database. The committee concludes that all three of the HST robotic servicing subsystem developments have significant schedule shortfalls, ranging from 18 months for the DM to 39 months for the EM plus RM, when compared to successful missions of similar complexity. The committee notes that even more significant is the fact that all of the 39-month HST robotic servicing mission options (even the DM alone) fall very close to the statistical sample of failed or partially failed missions.

The committee not only evaluated the HST project's schedule plan, but also reviewed the findings of both the Aerospace Corporations "Hubble Space Telescope (HST) Servicing Analyses of Alternatives" and NASA's Independent Program Assessment Team (IPAT) reports performed for NASA, as presented to the committee. The committee concurs with the findings of both of these groups that there is no precedent for a 39-month development schedule for a mission as complex as the baseline HST robotic servicing mission. In fact, the committee agrees with the Aerospace Corporation findings, which suggest that a successful mission of this level of complexity would require a nominal development time of the order of 65 months.

FINDING: The proposed HST robotic servicing mission involves a level of complexity that is inconsistent with the current 39-month development schedule and would require an unprecedented improvement in development performance compared with that of space missions of similar complexity. The likelihood of successful development of the HST robotic servicing mission within the baseline 39-month schedule is remote.

System Level Test and Validation

In addition to issues with the overarching system engineering and the lack of adequate development schedule time, another critical dimension for ensuring mission success is performing sub element, element and integrated systems testing. It is not clear that there is time in the current schedule to accomplish the necessary systems testing, particularly at the more complex integrated level. Nor is it clear that the end-to-end mission scenarios can be replicated in ground testing to validate the operations plans, which in turn requires the program development plan to build quality into all elements of the program at the subsystem and component level. The committee was shown a laboratory demonstration of the elements of the HST servicing mission at GSFC. This demonstration was at a TRL of 4: "Component and/or breadboard validation in a laboratory environment." Although some of the hardware for the proposed mission is at TRL-9, other components are not. Further, the committee found no evidence of systems integration beyond TRL-4.

The current 39-month schedule, as presented to the committee, has no real margin. As a minimum, this will preclude resolution of any serious problems that are discovered in final system test or will have major schedule and cost impacts, or will require a reduction of testing, which in turn likely will increase mission risk.

To improve chances for success under these circumstances, the program manager would require considerable latitude in authority and budget support from NASA headquarters. Parallel developments and alternative sourcing of critical components would need to be considered. For those critical components where alternative sourcing is impractical, increased management focus would need to be maintained to ensure success. Clearly if the project has adequately performed the upfront system engineering, prior to committing to a design implementation, which identified all of the risk items along with mitigation strategies; those considered high risk and without an acceptable mitigation strategy would be cause for pursing a completely different implementation solution. The servicing schedule baselined by the project has led them to commit to hardware development without yet completing the development of a complete risk analyses and mitigation plan and as a minimum the schedule for component development and sourcing would require acceleration to allow for thorough system testing and validation.

The program would require an adequate budget to accomplish this project, including a substantial management reserve to be used at the program manager's discretion. The Project informed the committee that their cost estimates indicated a requirement of close to a billion dollars for this effort. The committee has subsequently learned that NASA completed an independent cost estimate and is predicting costs of more than $2 billion. Although the committee does not have insight into the composition of these latest cost estimates, the inclusion of a robust management reserve will be critical to achieving a successful outcome. The committee points out that the Defense Science Board, led by Thomas Young, recently completed a 2-year review of national security space programs.[5] One of the findings of the Young panel was that the lack of budget flexibility was one of the chief reasons that complex space development programs were unsuccessful.

ASSESSMENT SUMMARY

The HST robotic servicing technical plan has significant risks. The initial risk is that of being able to develop the needed capability in the program in order to be able to conduct a mission to service Hubble on a schedule that would preclude a significant gap in the science program. The second risk is to effect a successful vehicle launch to the desired orbit, and to conduct a successful rendezvous. The third risk involves proximity operations and grapple by the robotic spacecraft. A fourth risk is being able to

[5] Department of Defense (DOD), 2003, *Report of the Defense Science Board/Air Force Scientific Advisory Board Joint Task Force on Acquisition of National Security Space Programs*, Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, DOD, Washington, D.C.

successfully execute the combination of complex autonomous and robotic activities required to actually accomplish HST revitalization and instrument replacement. Finally, the fifth risk is that the robotic mission lacks the flexibility to accommodate unforeseen Hubble equipment failures that may occur before the mission is executed and without significantly adding complexity and schedule delay to an already high risk robotic servicing technical and program plan.

There is some human intervention in the proposed robotic plan through teleoperation, and there may even be the potential for some reprogramming of robotic systems during flight as has been carried out with Mars landers and rovers. However, in general the robotic mission will of necessity be rigid in its design and in its ability to cope with unplanned anomalies such as those that have been encountered during each of the four previous shuttle servicing missions.

CONCLUSION: The very aggressive schedule for development of a viable robotic servicing mission, the commitment to development of individual elements with incomplete systems engineering, the complexity of the mission design, the current low level of technology maturity, the magnitude of the risk-reduction efforts required, and the inability of a robotic servicing mission to respond to unforeseen failures that may well occur on Hubble between now and the mission, together make it unlikely that NASA will be able to extend the science life of HST through robotic servicing.

RELEVANCE TO NASA'S SPACE EXPLORATION INITIATIVE

A robotic serving mission would provide GSFC with experience that could help NASA move toward robotic space exploration. Many technologies that are currently at TRL 7 or lower will be tested, potentially resulting in TRL 9 ratings by the time of mission execution. However, the algorithms, software, and much of the hardware that would be used in this proposed HST mission will have to be tailored to the specific needs of capturing and grappling a non-cooperative target. Further, assembly and disassembly tasks will need to be performed on a premier scientific spacecraft that was never designed for robotic servicing. Future robotic missions will presumably be designed for robotic deployment and servicing from the outset, and will therefore require a different set of robotic technologies.

The space exploration initiative will require the ability to robotically perform satellite servicing in deep space. In such an initiative, the target and the robotic spacecraft would both be designed to common interfaces with the necessary targets, fiduciaries, etc., to enable the robotic activities. Since the Hubble was designed for astronaut servicing, there are no such common interfaces. As such, it is unlikely that there will be significant engineering commonalities between the robotic servicing of Hubble and the essential robotic elements that would be specifically incorporated in a space exploration program.

A more detailed discussion of the comparative risk between a robotic servicing mission and a shuttle mission to HST is presented in Chapter 7.

FINDING: Many of the concerns raised by the committee regarding the risk of attempting to robotically service the Hubble telescope could be mitigated for future programs through planning for robotic servicing in the initial spacecraft design.

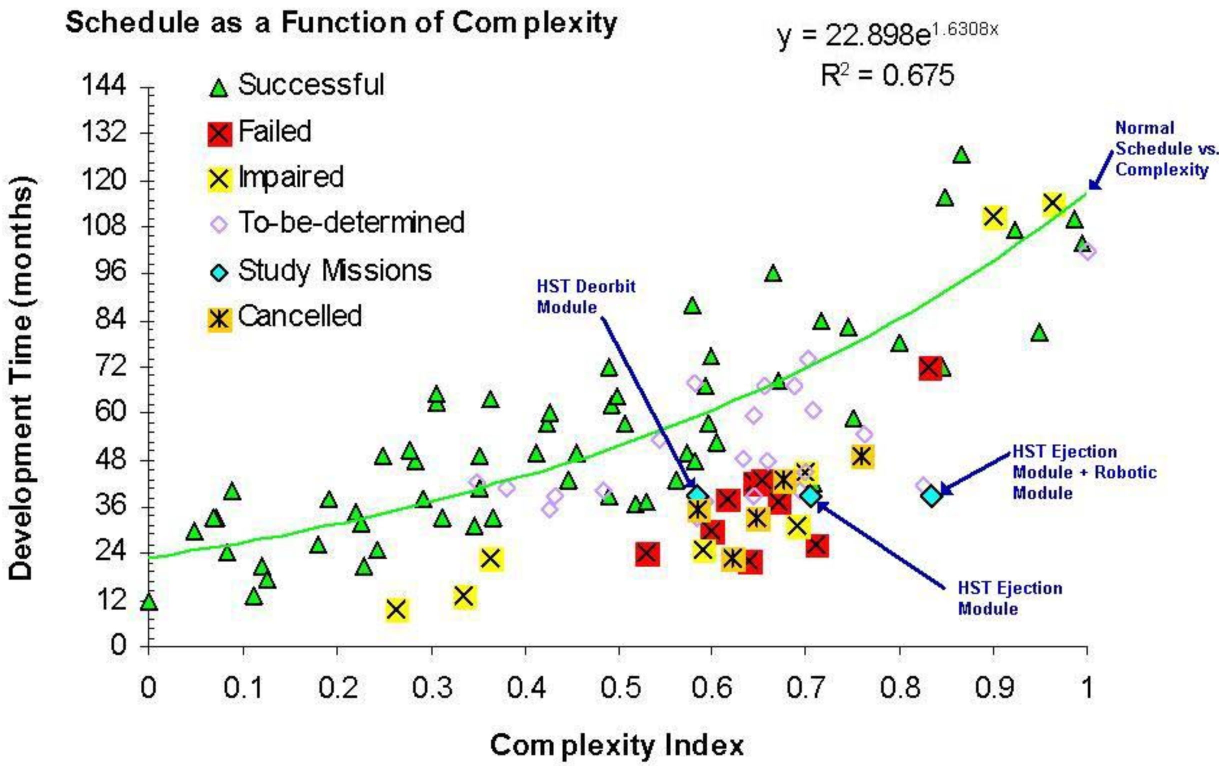

FIGURE 5.1 Hubble Space Telescope robotic servicing alternatives shown in comparison with Aerospace Corporation's historical database of development schedules for satellite missions of varying complexity and outcome. There is no successful historical precedent for a 39-month development schedule for a mission as complex as HST robotic servicing.

6
Space Shuttle Servicing of Hubble

INTRODUCTION

The Hubble Space Telescope (HST) was specifically designed to be serviced by space shuttle astronauts on an approximate 3 to 6 year cycle (also see Chapter 2). As noted in Chapter 2 and more thoroughly addressed in section “Relevant Space Shuttle Mission Successes” below, HST has been serviced four times and each servicing mission has fully met its objectives. Each mission improved the observatory capabilities and enhanced reliability while also satisfying the overriding servicing maxim of “do no harm.”

This chapter examines certain mission viability factors, other operational considerations, relevant prior servicing missions successes, and mission and crew safety risk considerations of servicing HST using the space shuttle during the flight operations that will follow the return to flight following the Columbia accident.

REQUIREMENTS AFFECTING THE VIABILITY OF A SHUTTLE MISSION TO HST WHILE MEETING THE CAIB AND NASA RETURN-TO-FLIGHT REQUIREMENTS

The committee takes as its starting point that NASA will meet the Columbia Accident Investigation Board (CAIB) and NASA requirements for the International Space Station (ISS) shuttle missions, and that the ISS shuttle missions are viable. The committee makes no determination or judgment as to whether the ISS missions are worth the human risk, but accepts the implied assessment from NASA that they are. Based on this assumption, this chapter assesses the differences between a shuttle mission to the ISS versus a shuttle HST servicing mission. NASA is currently planning 25 to 30 missions to the ISS to complete its assembly following return to flight (RTF).

CAIB Requirements

The orbiter Columbia was lost on February 1, 2003, during the re-entry of flight STS-107. After its loss, the CAIB was formed, chaired by retired Navy Admiral Harold Gehman. The CAIB formally reported its findings in an August 2003 report that contained 29 recommendations. Fifteen of these recommendations were identified as those that should be met prior to RTF. They can be found in their entirety in Chapter 11 of the *Columbia Accident Investigation Report*, Volume One. The CAIB recommendations were stated as a desired end result, the report did not specifically identify how each of them were to be achieved.

NASA is focusing the RTF effort on the ISS mission and has chartered the Return to Flight Task Group to review and evaluate the agency’s compliance with all RTF recommendations.

The CAIB requirements applicable to the viability of a space shuttle mission to the HST are quoted as follows: (There are only two CAIB requirements that are directly applicable to the viability of a space shuttle servicing mission to HST.)

CAIB Requirement 6.4-1[1]

For missions to the International Space Station, develop a practicable capability to inspect and effect emergency repairs to the widest possible range of damage to the Thermal Protection System (TPS), including both tile and reinforced carbon-carbon (RCC), taking advantage of the additional capabilities available when near to or docked to the International Space Station.

For non-Station missions, develop a comprehensive autonomous (independent of Station) inspection and repair capability to cover the widest possible range of damage scenarios.

Accomplish an on-orbit Thermal Protection System inspection, using appropriate assets and capabilities, early in all missions.

The ultimate objective should be a fully autonomous capability for all missions to address the possibility that an International Space Station mission fails to achieve the correct orbit, fails to dock successfully, or is damaged during or after undocking.[2]

CAIB Requirement 4.2-4[3]

Require the Space Shuttle to be operated with the same degree of safety for micrometeoroid and orbital debris as the degree of safety calculated for the International Space Station. Change the micrometeoroid and orbital debris safety criteria from guidelines to requirements.

Additional NASA Requirements

NASA has determined that it is insufficient for RTF to simply meet the CAIB recommendations and has concluded that it should go beyond CAIB requirements to increase crew safety. Additional applicable NASA RTF activities that affect the viability of an HST mission follow:

Space Shuttle Program Action SSP-3—Contingency Shuttle Crew Support (CSCS) [Safe Haven]:[4]

NASA will evaluate the feasibility of providing contingency life support on board the International Space Station (ISS) to stranded Shuttle crewmembers until repair or rescue can be affected.

Space Shuttle Program Action SSP-2—Public Risk of Over-flight:[5]

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[1] Columbia Accident Investigation Board, *Report, Volume I,* August, 2003, p. 174. Available online at http://www.nasa.gov/columbia/home/CAIB_Vol1.html.

[2] The committee interprets this statement from the CAIB to require an autonomous capability (if the mission fails to rendezvous with the ISS) on an ISS mission that could also be used on a mission other than ISS.

[3] Columbia Accident Investigation Board, *Report, Volume I,* August, 2003, p. 95. Available online at http://www.nasa.gov/columbia/home/CAIB_Vol1.html.

[4] NASA, *Implementation Plan for Space Shuttle Return to Flight and Beyond,* p. xxvii. Available online at www.nasa.gov/news/highlights/returntoflight.html.

[5] NASA, *Implementation Plan for Space Shuttle Return to Flight and Beyond,* p. xxvii. Available online at www.nasa.gov/news/highlights/returntoflight.html.

The Space Shuttle Program will evaluate relative risk to all persons and property underlying the entry flight path. The study will encompass all landing opportunities from each inclination to each of the three primary landing sites.

NASA Administrator's Considerations

In the committee's discussions with the NASA administrator, it was clear that he considers that three key elements differentiate a shuttle mission to ISS from a servicing mission to Hubble; these elements determined his overarching rationale for cancellation of the shuttle HST servicing mission:

(a) Crew Safety—Additional crew risk incurred on an HST mission versus an ISS mission.

(b) Time and Resource Consideration—The additional time and resources required to provide the desired inspection and repair on a non-ISS mission.

(c) Disciplined Implementation of Requirements —The discipline of fully implementing the CAIB and additional NASA Shuttle program requirements.

Additional Considerations for a Space Shuttle Mission to HST

In his letter to Senator Barbara Mikulski dated March 5, 2004, the CAIB Chairman, Admiral Gehman, amplified the intent of the Board by stating, "We called for a less technically challenging inspection capability for non-ISS missions. Do the best you can." Due to the capability required to detect and repair of TPS damage on an HST mission, the CAIB clearly recognized this additional difficulty, but did not state any requirement that precluded a non-ISS mission.

The committee believes that Admiral Gehman's phrase "Do the best you can" means NASA's best effort to meet the CAIB requirements while maintaining a balanced consideration of the risk mitigation provided by the effort.

NASA's Response to Recommendations

NASA has publicly stated that the agency intends to comply with all of the CAIB recommendations, and has initiated a comprehensive program to address CAIB recommendations and NASA RTF requirements.

Design changes are being implemented to reduce ascent debris to acceptable limits, and improved ground-based and airborne systems are being implemented to image the ascent phase of the launch. Cameras installed on the external tank (ET), the solid rocket boosters, and the orbiter will provide additional imagery of the TPS during ascent. Following separation of the ET, and once the orbiter is on orbit, the shuttle remote manipulator system (SRMS) with an attached orbiter boom sensor system (OBSS) will inspect the TPS for damage.[6]

On ISS missions, inspections will also be accomplished by the ISS crew during orbiter approach. Following docking, inspections will be by ISS equipment and/or extravehicular activity (EVA). TPS repair techniques are being developed to permit repair to both tile and RCC components. Initially, TPS repairs are planned while the orbiter is attached to the ISS using the SRMS to position the orbiter relative to the ISS to provide an astronaut repair work station. After the ISS Node 2 is deployed (currently scheduled on the eighth flight following return to flight), the SRMS will no longer be able to reach the ISS grapple fixture and so different procedures will have to be developed.

[6] The OBSS is an integrated system being produced to attach to and augment the existing Shuttle.

The SRMS/OBSS is an integrated system that consists of the normal SRMS and an attached boom (the OBSS). The system consists of the following:

a. The normal SRMS with its options for television cameras on the end effecter and the elbow. The SRMS can be used as stand alone or with the OBSS attached.
b. A 50-foot extension (the OBSS) with its supporting electro-mechanical infrastructure in the Shuttle payload bay and crew cabin.
c. Two sensor packages attached to the end of the OBSS that can be used to image the orbiter TPS.
    1. Sensor package 1 (primary) consists of an Intensified Television Camera (ITVC) (black and white, high resolution, low light capability) and a Laser Dynamic Range Indicator (LDRI) (3-D Laser Mapper to detect/measure the extent of damage to tile and RCC surfaces). These two imagers are mounted on a standard orbiter pan and tilt unit to enhance and expedite the total acreage survey and/or detailed damage inspection of the orbiter surface.
    2. Sensor package 2 (back up) consists of a single laser camera system (LCS) with a fixed field of view perpendicular to the long access of the boom and mounted with vibration isolation apparatus.
d. Rated in qualitative terms of level of resolution, the ITVC is good, the LDRI is higher, and the LCS is highest.

THE VIABILITY OF A SHUTTLE MISSION TO HST WHILE MEETING THE CAIB AND NASA RTF REQUIREMENTS

Based on NASA briefings and materials supplied by the Space Shuttle program, the following represent the committee's considerations for the viability of a space shuttle mission to HST that will satisfy the CAIB as well as the additional NASA requirements.

On-Orbit Inspection Planning and Flexibility

An ISS mission incorporates a series of inspections that take advantage of the observations of astronauts onboard the ISS as well as the station imaging resources to minimize the time required for inspection. NASA is planning the following inspections for an ISS mission: The shuttle SRMS/OBSS will be used in inspecting the wing leading edge (WLE) RCC early in flight. Prior to docking at the ISS, the shuttle will execute a rotational pitch maneuver to permit visual observation and photography of the tile areas by ISS astronauts using digital cameras. The data will be transmitted to the Mission Control Center for evaluation. After docking, the SSRMS and window views will be used for visual observations and digital photography, if required.

Detailed inspection of areas of concern found during the ISS observations will be performed, if warranted, using the SRMS/OBSS. If required, a spacewalk can also be carried out for a close-up inspection. NASA is currently developing EVA inspection techniques.

On an HST mission, SRMS (standalone) and the SRMS/OBSS, without augmentation from any other system, could be used to do a complete inspection.

NASA reported that the inspection on an HST servicing mission would require more time than one on an HST mission. This increased time results from not having the advantage of an inspection from astronauts and from the imaging resources onboard the ISS. NASA has not done a complete timeline to determine the exact amount of time required for an ISS inspection. The committee believes that it is possible to develop additional sensors that would reduce the time required to perform an inspection on a shuttle HST mission. The options range from new techniques to scaled versions of the current sensors to fill the SRMS coverage gap.

The committee concludes that there are at least two approaches that could satisfy the inspection requirements during a shuttle HST servicing mission:

1. The resources and procedures developed for the ISS missions could be used to accomplish the inspection and to add the required time to the HST timeline as follows:

- Use the SRMS/OBSS to inspect the wing leading edge (WLE).
- Use the SRMS (standalone) to inspect areas where it provides adequate resolution for a large portion of the acreage tile. The remaining cannot be imaged at the required resolution with the SRMS due to limitations on its physical reach and field of view of its wrist camera.
- Complete the remaining inspection of the acreage tile with the SRMS/ OBSS.
- A detailed inspection could be accomplished via a spacewalk as a backup if deemed necessary.

2. Develop additional sensors to reduce the inspection time.

- Use the SRMS/OBSS to inspect the WLE RCC.
- Use the SRMS to inspect areas where it provides adequate resolution.
- Use the additional sensors to inspect the remaining areas.
- Use the OBSS to inspect areas of concern if required and available.
- A detailed inspection could be accomplished via a spacewalk as a backup if deemed necessary.

The committee notes that implementation of either approach would satisfy the CAIB and NASA requirements for shuttle inspection. The ultimate objective would be a fully autonomous capability for all shuttle missions in order to address the possibility that an ISS mission fails to achieve the correct orbit, fails to dock successfully, or is damaged during or after undocking.

FINDING: A complete inspection of the orbiter thermal protection system can be accomplished on a shuttle servicing mission to HST using the SRMS and the SRMS/OBSS.

On-Orbit Repair Capability and Limitations

To repair damage to the outer surface of the shuttle while it is on orbit, one or more astronauts must make the repair during a space walk. The astronaut must be able to access the area to be repaired and have a stable work site at the area. For return to flight to the ISS, the shuttle can be positioned using the SRMS to an attitude that allows access to the work site from the ISS, either directly or from the SSRMS.

However, after the installation of the Node 2 on the ISS (currently scheduled for the eighth flight after RTF), due to the inability to reach the ISS grapple fixture, the SRMS will no longer position the shuttle for inspection and repair. A different work site plan will be required after the eighth flight after RTF. NASA is currently developing a technique using the SRMS/ OBSS to position the crew at the work site. This technique could also be used on an HST mission. Since this technique provides access to the repair work site independent of ISS, it can be used on all flights or on an ISS flight that fails to achieve the correct orbit or to dock successfully. Therefore, it will satisfy the repair site access portion of the "fully autonomous" capability requirement recommended by the CAIB.

FINDING: The orbiter thermal protection system repairs can be accomplished on a shuttle servicing mission to HST following the development of worksite and repair techniques for ISS to meet the CAIB and NASA requirements.

Safe Haven and Crew Rescue

The CAIB did not make a recommendation for a safe haven capability for future space shuttle missions. Nevertheless, NASA has recognized that ISS missions provide some capability for a safe haven, and has base-lined a Contingency Shuttle Crew Support (CSCS/Safe Haven) requirement for the first two flights following RTF. In the future, the program will consider extending this requirement.

ISS Safe Haven

The ISS can be used as a safe haven to provide additional time to deal with emergency problems. If the shuttle is docked to the ISS, NASA analysis indicates that the astronauts could be housed in the ISS for 30 to 90 days beyond the shuttle mission timeframe. This conclusion assumes (1) that the zero-fault-tolerant[7] ISS life support system (i.e., ability to support 10 people) is available, and (2) that sufficient supplies (food, water etc.) have been pre-positioned aboard ISS.

The additional time provided by the ISS safe haven capability, assuming it is available, provides the following attributes:

- Additional time to repair the damaged shuttle and prepare for shuttle for re-entry.
- Additional time to make modifications to the rescue vehicle and its cargo if required and to launch the rescue shuttle.
- Schedule relief for the shuttle launch team.

Although these attributes provide desirable operational flexibility, use of the ISS safe haven also results in a strategy that has significant risks. First, the ISS's ability to support 10 people for 30 to 90 days depends on a zero-fault-tolerant life support system that may fail at any time. This also requires the pre-staging of adequate resources on the ISS to support 10 people for the desired time.

Important ISS areas that are zero-fault-tolerant or that have negative margins are oxygen generation, carbon dioxide removal, waste removal, water supply and condensate processing.

FINDING: The ISS safe haven offers operational flexibility and time to adapt to real-time problems in the case of a critical ascent impact event that is both detected and repairable, or that affords the option of a shuttle rescue mission. However, the availability of the ISS safe haven is zero-fault-tolerant, requires significant pre-positioning of supplies, and, therefore, has significant risks due to its limited redundancy and margins.

HST Shuttle Servicing Mission Safe Haven

On an HST shuttle mission, safe haven could be provided by an extreme power down of the shuttle. The duration is limited, due to critical consumables, to between 17 and 30 days depending on when the contingency power-down is done. This would require the launch of a rescue vehicle within days after launch of the servicing shuttle that encountered the problem.

[7] Zero-fault-tolerant means any single failure renders the system in-operative and results in loss of the system's function.

However, during the committee deliberations, other options for increasing the safe haven time at HST surfaced.[8]

Extended Duration Orbiter Safe Haven—Following the Challenger accident, NASA developed an Extended Duration Orbiter (EDO) capability using additional cryogenic tanks. This permitted the shuttle to fly up to 15 additional days in an extreme powered-down condition. NASA reported that orbiter Vehicle 104 (OV104) and OV105 are equipped to utilize the EDO system while OV103 is not. Outfitting 103 for EDO would provide highly desirable scheduling flexibility if a mission required the EDO's capability. However, it would take 6 months of work to install the EDO system in the orbiter processing facility. The oxygen and nitrogen tanks are long lead items that would take 24 months to design, build, and certify. The completed hardware is required at KSC 8 months before flight. Therefore, the earliest the EDO could fly is 2.8 years from project initiation.

Space Shuttle Rescue Mission As Integral to All Safe Haven Concepts

A shuttle rescue mission is part of the NASA requirements in planning for the ISS mission. It entails being prepared to launch a rescue shuttle to retrieve the stranded crew of a damaged shuttle. On an ISS mission, the ISS safe haven is expected to provide the additional time required to mount the rescue. This would allow the orbiter to be in a normal flow in the orbiter processing facility at any call up for rescue. A shuttle rescue mission of an HST crew would require launch and rescue within 17 to 30 days, depending on when an emergency power down of the shuttle is done, while the ISS mission nominally provides 30 to 90 days.

If rescue is deemed mandatory for a single shuttle mission to service HST, the rescue vehicle would need to be pre-positioned on the launch pad to allow launch as soon as possible. The workload for launch preparation in such a case would be different. However, with careful planning and preparation, the committee believes it is well within the capability of the shuttle team.

The shuttle processing team is regularly processing up to three orbiters at any time. Planning, scheduling, and prioritizing the total work at KSC should allow the processing of an early rescue launch without an "unprecedented workload." The shuttle program has experienced several periods where balancing workload and the short-term manifest has overcome workload challenges. For example, in July of 1995, STS-71 was launched 14 days following STS-70.

To minimize the impact to downstream flight, this strategy would also require careful manifesting of rescue hardware and ISS hardware in order to allow proceeding with the next ISS flight in an orderly fashion. By changing out the required cargo on the launch pad, NASA has indicated that an ISS mission could be launched 30 days after the rescue mission is called off. The prompt initiation of limited mission planning for a shuttle servicing mission to HST, including the requirement for parallel processing for a rescue orbiter on the second launch pad, will assure maximum flexibility and minimum resource impact.

FINDING: An HST shuttle rescue mission can be ready on the second launch pad. There would be some costs and ISS schedule delays, principally because of the impact of parallel orbiter processing. Limited time would be available to execute a rescue.

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[8] In addition to the safe haven consideration discussed in this section it came to the committee's attention that commercial companies have suggested options to launch a "safe haven" vehicle into the HST orbit in order to provide a longer term capability. The committee understands that NASA has been provided these proposals, which will naturally require a balancing of crew safety, risk reduction, cost and schedule, etc., if any are pursued.

Micro-Meteoroid Orbital Debris Risks

The micro-meteoroid orbital debris (MMOD) risks to the shuttle are different for an ISS and an HST flight. The debris density at the HST altitude (~570 km) is higher than the density at the ISS altitude (~355 km), resulting in a higher risk of collision at the HST orbit. On the other hand, the orbiter attitude during an HST mission affords better protection from the debris. When altitude and attitude considerations are combined, the HST flight has a smaller chance of catastrophic debris collision than the ISS flight. However, NASA is currently working to modify the ISS attitude to reduce the collision risk on an ISS mission and to validate the collision and damage models to better understand this problem. When this work is completed, NASA expects that the MMOD risk will be smaller on an ISS mission. The committee expects that the ultimate differences will be small and will not be a significant contributor to the risk factors.

NASA plans considerable effort on the MMOD issue prior to resuming shuttle missions in order to develop a better understanding of the MMOD risks and to develop the flight rules to control the risks.

Public Risk of Overflight

The shuttle deorbit burn and subsequent re-entry and landing can be accomplished from either ascending or descending orbital tracks. The tracks have been designed to optimize reception of telemetry data, structure the crew work/rest cycle, provide daylight landings, and deal with the weather at the landing site. The combination of landing site location and the choice of ascending (vehicle traveling northeast) or descending (vehicle traveling southeast) re-entry tracks determine the amount of populated landmass that is overflown. The populated landmass overflown during entry is the driver for public risk. Since the Columbia accident, this became a heightened concern.

NASA is currently developing mission rules to manage the entry flight path in order to deal with the public risk of overflight. The committee is confident that flexibility of ascending orbits versus descending orbits and landing site selection will allow the development of flight rules that will result in comparable public risk of over flight for both the ISS and HST missions.

Summary of Viability for Meeting Both the CAIB and NASA Requirements

Considerations for the viability of meeting the CAIB NASA requirements have been discussed in this section. Inspection techniques developed for ISS missions can be used to accomplish the TPS inspection requirements. The committee believes that additional work could be done to reduce the time required for implementation of the shuttle HST servicing mission. Repair requirements can be accomplished on an HST mission once worksite positioning techniques are developed. Techniques currently being developed for after node 2 installation on the ISS could also be used on a shuttle HST servicing mission. The committee believes an emergency power down as soon as a credible indication of a catastrophic problem is detected will afford additional HST mission safe haven time. Shuttle rescue would involve pre-positioning the rescue shuttle on the launch pad ready for rescue and performing the necessary mission preparation. The committee believes that once the scheduled work of mission rules and procedures is completed, the MMOD risk and public risk for over flight will not be a consideration.

FINDING: Meeting the CAIB and NASA requirements (relative to inspection and repair, safe haven, shuttle rescue, MMOD, and risk to the public) for a shuttle servicing mission to HST is viable.

ADDITIONAL OPERATIONAL CONSIDERATIONS

In addition to meeting the CAIB and NASA RTF requirements, the following considerations affect the ability to execute a shuttle HST servicing mission.

Shuttle Rescue Operations Complexity

Crew rescue on an HST mission would require planning and training for a complex set of EVA operations to affect the transfer of the crew. In an example scenario provided by the Shuttle Program Office, the rescue shuttle would launch within days after the HST servicing mission and would rendezvous with the damaged shuttle. After rendezvous, the damaged shuttle would grapple the rescue shuttle with the robotic arm. Three spacewalks would be conducted to transfer the rescued crew and launch escape suits. Two of the spacewalks would be conducted while grappled, while the third would be conducted while flying in formation (a crewperson is required to un-grapple the rescue vehicle from the damaged vehicle). The rescue shuttle's SRMS would be used to transport the crew members from the damaged shuttle to the rescue shuttle. The first two EVA's would be long spacewalks involving two depressurizations and re-pressurizations of the shuttle airlock. The third spacewalk would be conducted while flying formation since the SRMS of the damaged shuttle must be un-grappled before the last crew person leaves the vehicle.[9]

The shuttle has rendezvoused with and grappled numerous satellites, including the HST four times, without any major problem. The rendezvous and grappling of the damaged shuttle is well within the experience base and the capabilities of the shuttle program.

The spacewalks that transfer the flight crew are complex and result in a higher risk than the transfer on an ISS mission. However, the shuttle program has considerable experience in complex spacewalks as described below in "Relevant Space Shuttle Mission Successes."

FINDING: The extravehicular activities (spacewalks) for transferring the crew from a damaged vehicle on a shuttle HST flight, although complex, are well within the experience base of the shuttle program.

HST Manifesting Options

The selected flight position of an HST servicing mission in the space shuttle manifest is crucially important, since a balance must be struck between shuttle RTF, construction and logistics requirements of the ISS, and the necessity to preserve and upgrade the HST science mission before failures aboard HST make that impossible.

NASA reported to the committee that, if flown, the HST mission would be manifested after the completion of the twelfth ISS flight currently scheduled in July 2007). This gives priority to the International Partner element deployments to the ISS. If the RTF launch date of March 2005 slips significantly, or if subsequent ISS mission delays are incurred, this location in the shuttle schedule would put the HST at risk (see Chapter 4).

After the shuttle returns to flight, the first two missions (FL1 and UFL1.1, both to the ISS) are planned to be devoted to RTF activities and to initial ISS logistics and utilization. In discussing the ISS planning for subsequent flights with NASA, the committee was informed that the critical flights for the ISS are those that ensure its power and thermal configuration (flights 12A, 12A.1, 13A and 13.A.1).

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[9] Randall Adams and Wayne Hale, NASA Johnson Space Center, "Shuttle and Mission Operations: Requirements for Human Servicing Mission," presentation to the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope, June 2, 2004.

Inserting an HST servicing mission before this sequence is complete would not be advisable. Therefore, the earliest opportunity to fly the HST mission is the seventh flight after RTF (currently scheduled for July 2006). This would provide the best opportunity for HST mission success, but would delay the completion of the ISS assembly and International Partner element deployment by about 4 to 6 months. The exact time delay will depend on the approach to the HST mission, the resources expended to prepare for the HST mission and the next mission, and the planning for processing at KSC. Implementation of an HST flight on the seventh mission will require careful ISS logistics planning and associated manifesting.

FINDING: To avoid putting the Hubble at risk and to maintain continuous science operation the HST servicing mission could be flown as early as the seventh flight after return to flight without a critical operational impact on the ISS.

RTF Workload

NASA informed the committee that the agency is concerned about the time and effort required to attain the level of additional safety that is required to successfully complete the RTF, and is further concerned that adding the additional burden of a non-ISS flight to the flight manifest could seriously threaten its capacity to return to flight in a timely fashion. Although much of the mission planning for a shuttle HST mission was well along prior to the announcement of cancellation of the HST SM-4 mission, additional planning and training for the crew and ground team still remains to be accomplished in order to prepare for the additional activities to meet the CAIB and NASA requirements on the HST mission. As examples, the on-orbit TPS inspection plan would be different from those on an ISS mission. Additional repair site stabilization techniques and/or hardware may be required, and contingency planning for the transfer of a stranded crew to a rescue mission vehicle will require the initiation of new planning and training.

While recognizing that additional work must be done to position the program to perform an HST servicing mission, the committee believes that the earliest HST servicing mission could occur on the seventh mission following RTF and that the major HST workload can come after the workload required for RTF.

FINDING: Major HST mission preparation work for a shuttle servicing mission to HST can be deferred until after return to flight. This would avoid a significant expenditure of human resources until the shuttle is flying again.

HST De-orbit Module on a Shuttle Servicing Mission

The committee did not give consideration to the option of flying a HST de-orbit module on a shuttle servicing mission because of the possible mission complications, the additional time required for mission preparation, potentially excessive cargo weight/volume, and possible problems with de-orbit module reliability given the required long stay on orbit before de-orbit.

However, during NASA planning for a shuttle HST servicing mission, an in-depth assessment should be conducted to determine if there is any merit to flying a de-orbit module on the shuttle servicing mission rather than conducting an end-of mission robotic deorbit.

TIME AND RESOURCES NEEDED TO OVERCOME UNIQUE TECHNICAL OR SAFETY ISSUES ASSOCIATED WITH HST SERVICING

After the cancellation of the shuttle HST servicing mission, NASA stopped all work on a non-ISS mission and is concentrating on RTF and the ISS missions. As a result, the NASA data that were available to the committee to allow it to assess the time and resources required to overcome any unique technical or safety issues associated with HST servicing required to meet the CAIB and NASA requirements was limited to qualitative statements provided by the Shuttle Program Office and other NASA personnel. The actual amount of unique time and resources required to fly an HST versus an ISS mission depends on the approach selected to implement this single HST mission. The committee believes that the range of possible options available to NASA is broad and includes the following:

- Implement and adapt the ISS-developed inspection and repair capability on the HST flight. Do not do additional major inspection and repair procedures development to support the single HST mission.
- Focus on inspection and repair capability and forego the rescue capability. Current plans indicate that such an approach would require either adding time to the inspection task with the shuttle OBSS or augmenting the OBSS IVTC with new/additional sensors to provide an overview inspection similar to the ISS capability. This would also require providing techniques and/or hardware to insure the OBSS could be certified to serve as a worksite for TPS repair.
- Focus on the rescue capability while augmenting the inspection capability to the minimal extent deemed acceptable. This would require parallel orbiter processing at KSC to provide a second launch-ready shuttle as well as simultaneous, equal-priority crew training at JSC for both the HST and rescue mission crews.
- Focus on both a full repair capability and a rescue capability.

Ultimately the decision on the approach to an HST mission is the responsibility of NASA. Although all options may not meet the full intent of the CAIB and NASA requirements, the committee believes that after consideration of an appropriate crew safety risk analysis for a single HST mission, any of the above options would be acceptable. Regardless of the NASA approach taken on an HST flight, the committee also believes, based on its accumulated experience, that the increases in required resource and time impacts would be small compared to the total cost of servicing the HST. Any of the approaches are within the framework of the shuttle program capacity and experience base.

FINDING: Compared to the total cost of flying a shuttle flight, the resources required to overcome unique technical or safety issues involved in flying a shuttle mission to HST are small and are well within the experience base of work done in the past to enable unique shuttle missions.

ADDITIONAL COSTS TO REINSTATE A SHUTTLE SERVICING MISSION

Detailed information on the cost of performing a servicing mission of HST using the shuttle was not available to the committee, but the committee did receive a portion of NASA's input to the Government Accountability Office (GAO),[10] which estimated costs as follows:

Hubble Project Costs	$614 million
Shuttle & ISS Program Costs	$1.1 billion to $1.8 billion
Total	**$1.7 billion to $2.4 billion**

[10] NASA, "Review of Hubble Space Telescope Servicing Mission Cost," letter report dated August 13, 2004, NASA, Washington, D.C.

The NASA letter report to the GAO notes that $400 million to $1.0 billion of the shuttle and ISS program's cost will be incurred in the last year of shuttle program life, currently targeted for 2010. The variations are due to marginal versus proportional annual cost accounting methods. The HST project costs of $614 million will be expended through 2012 for HST to sustain engineering, mission operations and analysis, and for delay of the de-orbit module to 2012. NASA's letter states that the estimated costs of standalone TPS inspection and repair capability ($260 million to $300 million) and development of standalone rescue ($290 million to $340 million) are due to the fact that " no design solution is currently available."

The committee believes that careful planning for, and implementation of, the additional HST-unique activities to meet the CAIB and NASA requirements will result in substantially lower actual costs to service the HST using the shuttle than those projected above. For example, the inspection techniques can be a direct derivative of the ISS techniques. The repair techniques could be, as discussed above, the same as those for the ISS after node 2 installation. The ongoing GAO assessment of shuttle servicing costs may provide greater insight into these questions when it is released at the end of 2004.

HST VERSUS ISS CREW SAFETY RISK

NASA reports that the agency is currently in the process of updating the Shuttle Probabilistic Risk Assessment (PRA) model which is planned to be available in late 2004. The agency was therefore unable to provide specific, quantitative risk difference information for examination by the committee. The data provided during the committee's discussions with NASA were based on engineering judgment and were qualitative, and in most cases specific elements of the HST mission risk were described as "higher risk" or "lower risk" (in comparing a ISS mission to a HST mission), but otherwise were not quantified.

Since the Columbia accident, NASA has been developing many safety improvements to be implemented prior to RTF and beyond. The committee reviewed progress on RTF issues, qualitatively assessed the risk reduction expected from the safety improvements for missions to HST and ISS, and qualitatively compared the risks of the two types of missions. The committee agrees that post-RTF missions to the ISS will have some safety advantage over an HST mission such as total time required to perform ascent damage detection and the availability of crew safe haven and rescue (see previous sections of this chapter).

However, the committee concludes that this post-RTF advantage will be small—because the need for such repairs and crew rescue will have been sharply reduced by elimination of critical ascent debris. That is, the NASA shuttle program's rationale for return-to-flight from the STS-107 mission failure is based on the identification and elimination of critical ascent debris. Critical ascent debris sources are defined as those that have an unacceptably high probability of liberation during launch, and have an aerodynamic transport mechanism that would permit the debris to impact a vulnerable location with enough energy to cause catastrophic damage to the TPS. Following flight certification for the improved external tank, NASA will consider the ascent debris risk to the shuttle TPS as acceptable. All other corrective actions are considered additional risk reduction measures. These include the on-orbit TPS inspections, repair capability, and safe haven for both the ISS and HST missions.

In a meeting with a sub-group of the committee that reviewed risk questions associated with a shuttle HST servicing mission, NASA personnel stated that the risks associated with the launch/ascent and entry/landing phases of any mission comprise the vast majority of the safety risks of a mission, and that these phases are comparable for the ISS and HST missions.

Therefore, in terms of risk to vehicle and crew, the committee concludes that the difference in risk of loss of the vehicle and crew between a single servicing mission to the Hubble and a single mission to ISS is extremely small. The committee further believes that adding a shuttle flight for an HST SM-4 mission adds a percent or fraction more to the total risk of losing astronauts in the course of completing the already planned ISS program.

FINDING: The shuttle crew safety risks of a single mission to ISS and a single HST mission are similar and the relative risks are extremely small.

RELEVANT SPACE SHUTTLE MISSION SUCCESSES

Human Response to Unforeseen On-Orbit Contingencies

As previously noted in "Avionics Reliability Model" in Chapter 4, the flexibility provided by astronauts is highly valuable in repairing unforeseen anomalies in the avionics systems of the HST (see findings in "Avionics Reliability Model"). Between 1984 and 1992, prior to the first HST servicing mission, there were five space shuttle missions in which astronauts were called upon to respond to unexpected scenarios in the conduct of spacewalks (or extravehicular activity (EVA)) or leading to EVAs. The five incidents are summarized below.

- **STS-41-C, April 1984.** The mission was planned to retrieve, repair and redeploy the Solar Maximum Mission (SMM) satellite, which was de-spun to enable the on-orbit work. During the attempt to capture the SMM using the manned maneuvering unit with an attached trunnion pin attachment device, the grapple mechanism failed to operate multiple times and an attempt by the extravehicular crewperson to stabilize the satellite by hand resulted in increased instability of the SMM. Following a night and day of re-planning on the part of the mission control and flight crews, the shuttle was flown so as to bring the SMM into close proximity of the shuttle payload bay where it was grappled using the SRMS. The SMM was subsequently berthed in the shuttle, repaired (a faulty attitude control system and one science instrument were replaced) and redeployed using the SRMS.[11]
- **STS-51-A, November 1984.** The mission was planned to rendezvous with and retrieve the Palapa B2 and WESTAR VI communications satellites that had failed to reach their operational orbits following failure of their upper stage rocket motors on a previous shuttle mission. When the EVA crewperson flew to the first satellite using the MMU and attempted to grapple it using a specially designed capture bar, the bar failed to fit properly and the satellite capture failed. Following re-planning by the mission control and flight crews, the shuttle was flown sequentially to re-rendezvous with each satellite and the satellites were literally flown into the cargo bay where EVA crewpersons, tethered in the payload and on the end of the RMS, manually grappled each satellite and docked them in the bay for the flight back to Earth. Each satellite was subsequently refurbished and successfully launched into service.[12]
- **STS-51-D, April 1985.** The mission was planned to deploy the SYNCOM IV-3 communications satellite. Following the deployment, it was determined that the satellite failed to activate as planned. The shuttle rendezvoused with the malfunctioning satellite and, while flying in close formation, two EVA crewpersons attempted to manually activate the power switch on the satellite utilizing a device that was fabricated on-board. The activation attempts failed, but the shuttle program had again demonstrated the ability of human crews to make a real-time response to an on-orbit contingency. There had been no EVA planned for this flight.[13]
- **STS-51-I, August/September 1985.** The flight was planned to rendezvous with and retrieve the errant SYNCOM IV-3 communications satellite left on orbit by STS-51-D earlier in the year. After

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[11] NASA, *STS-41-C National Space Transportation Systems Program Mission Report* (JSC-19642). NASA Johnson Space Center, Houston, Tex., May 1984.

[12] NASA, *First 100 Manned Space Missions*. NASA Kennedy Space Center Public Affairs Office, June 14, 1995. Available online at http://science.ksc.nasa.gov/shuttle/missions/51-a/mission-51-a.html.

[13] ibid. Available online at http://science.ksc.nasa.gov/shuttle/missions/51-d/mission-51-d.html.

the rendezvous was accomplished, two EVA crewpersons manually grappled the satellite, brought it into the payload bay for the installation of a new battery/starter mechanism, and subsequently manually redeployed the satellite for successful on-orbit operation.[14]

- **STS-49, May 1992.** This mission was planned to rendezvous with and retrieve an INTELSAT-VI communications satellite that had been left in a useless orbit from its earlier launch. In a never-before-done three-person EVA, the crew manually grappled the satellite as it was flown into the payload bay. The crew installed a replacement upper stage rocket motor while the satellite was in the shuttle payload bay and redeployed it for subsequent successful on-orbit operation.[15]

Space Shuttle Servicing Missions to the Hubble Space Telescope

To date, there have been four completely successful space shuttle servicing missions (SM) flown to Hubble. These missions have continuously enhanced the performance of HST, resulting in a huge increase in the data gathering capability of this observatory. The following are summaries of the accomplishments as well as some contingency responses that were necessary during the conduct of these four HST servicing missions.

STS-61 (SM-1), December 1993

SM-1 was the first of the HST servicing missions and its primary goals included the installation of the Corrective Optics Space Telescope Axial Replacement (COSTAR) to correct the spherical aberration that was discovered in the telescope's primary mirror weeks after its initial deployment in 1990. In the process of conducting five EVAs, the crew encountered six documented anomalous situations.[16]

1. Retraction of the positive axis solar array (+V2 SA) was halted when the crew visually detected slack in the blanket. The problem was caused by bowing and a kink in the outer bi-stem of the SA. The decision was made to manually remove and jettison the damaged array to avoid the risk to having an improperly stowed component in the shuttle payload bay during reentry and landing.
2. During initial attempts to close the –V3 aft shroud door on the HST, the EVA crew encountered alignment problems that prevented closure. The misalignment was subsequently corrected through the impromptu use of a payload retention device and the door was closed and locked.
3. In the process of examining the integrity of the HST, the EVA crew discovered two loosened sides of protective covering on the magnetic sensing system-2. A thermal blanket available elsewhere on the HST was wrapped on the magnetometers to protect them from further degradation from exposure to atomic oxygen and ultraviolet light.
4. On the second and fourth EVAs, two-way communications between an EVA crewperson and the orbiter crew was lost. Communications between this crewperson and the other two EVA crewmembers, however, remained good and both EVAs were continued using relay of communications.
5. When the primary deployment mechanisms of the new solar arrays were commanded to deploy, neither responded. An EVA crewperson manually deployed both of them.

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[14] ibid. Available online at http://science.ksc.nasa.gov/shuttle/missions/51-i/mission-51-i.html.

[15] NASA, Flight 047 STS-49 Mission Highlights. Available online at http://spacelink.nasa.gov/NASA.Projects/Human.Exploration.and.Development.of.Space/Human.Space.Flight/Shuttle/Shuttle.Missions/Flight.047.STS-49/.index.html.

[16] NASA, Space Shuttle Mission Report NSTS-08288, NASA Johnson Space Center, Houston, Tex., February 1994.

6. During the original SADE-1 removal, two connector screws and mounting clips became disengaged and were captured by the EVA crewperson. While removing SADE-1, a mounting screw also came loose and was retained.

When the EVAs were completed, the following operations had been successful completed:

- Installed COSTAR,
- Installed Wide Field Planetary Camera-2 (WFPC-2) as replacement for original instrument,
- Replaced both solar arrays,
- Replaced the solar array drive electronics (SADE),
- Replaced original magnetometers,
- Replaced co-processor for the flight computer,
- Installed two replacement rate sensor units (RSU),
- Installed two replacement gyroscope electronic control units, and
- Installed a Goddard High Resolution Spectrograph (GHRS) redundancy kit.

STS-82 (SM-2), February 1997

The second servicing mission to HST, the objective of this flight was to significantly upgrade the scientific capabilities of the observatory. All of the HST primary and secondary objectives for this mission were fully accomplished. Although originally scheduled for four EVAs, it was decided to conduct a fifth EVA for the purpose of repairing a damaged (torn) thermal blanket. The crew also fabricated patches that were installed to cover thermal blanket tears on HST bays 8 and 10. Both bays contained components requiring thermal protection. There were two documented anomalies during EVAs.[17]

1. During opening of the +V2 aft shroud doors on EVA-1, the bottom latch bolt only backed out 3 ½ turns (expected 6-8 turns) when the door was initially opened. Furthermore, during door closure another latch would not drive closed with the nominal tool setting. When the lowest latch was attempted, it also did not drive. The EVA crewperson increased the torque setting on the pistol grip tool to start both fasteners and then reset it to the planned torque.

2. When attempting to mate an electrical harness to the HST connector, the EVA crewperson noticed a bent pin in the corner on the short side. A spare harness was obtained from an onboard storage locker and installed successfully.

At the completion of the five EVAs on SM-2, the following tasks had been successfully accomplished:

- Installed Space Telescope Imaging Spectrograph (STIS),
- Installed Near Infrared Camera and Multi-Object Spectrometer (NICMOS),
- Installed a refurbished fine-guidance sensor (FGS),
- Installed Optical Control Electronics Enhancement Kit (OCE-EK),
- Installed solid-state recorder (SSR),
- Replaced reaction wheel assembly (RWA),
- Replaced data interface unit (DIU), and
- Replaced solar array drive electronics (SADE).

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[17] NASA, Space Shuttle Mission Report NSTS-37413, NASA Johnson Space Center, Houston, Tex., April 1997.

STS-103 (SM-3A), December 1999

The objective of this third HST servicing mission was to further upgrade the scientific capabilities of the observatory. Because the HST had gone into safe mode with the failure of a fourth gyroscope, the decision was made to divide the scheduled third mission into two missions in order to launch an earlier "emergency mission" to replace the failed gyros that had lead to the HST "going to sleep." From the time of the decision to fly the "emergency mission," it was planned, launched, and successfully accomplished in seven months. All the EVA tasks for this flight were fully accomplished over the course of the three EVAs. Only one EVA anomaly occurred and that was a failure of the power ratchet tool (PRT) during EVA-1. After unsuccessfully attempting to correct the problem with a change out of the batteries, the PRT was replaced with the pistol grip tool for the remainder of the flight.[18]

At the completion of SM-3A, the following had been successfully accomplished:

- Installed three new rate sensor units (six replacement gyroscopes),
- Installed batter voltage/temperature improvement kits,
- Installed a faster (486) main computer,
- Installed a next-generation solid-state data recorder,
- Installed a new S-Band single-axis transmitter-2 (SSAT2),
- Installed a replacement enhanced fine-guidance sensor (FGS),
- Installed new outer blanket layers (NOBL) on bays 9 and 10, and
- Performed the NICMOS valve-opening procedure in preparation for reservicing on next servicing mission.

FINDING: The shuttle mission planning process provides flexibility in final manifesting and mission execution that can be used to respond to known or unforeseen HST anomalies.

STS-109 (SM-3B), March 2002

This was the fourth of the HST servicing missions. Five EVAs were successfully conducted with no documented EVA activity anomalies.[19]

At the completion of the mission, the following had been accomplished:

- Replaced the original Faint Object Camera (FOC) with the Advanced Camera for Surveys (ACS),
- Installed solar array 3 (SA3), +V2 resulting in a 30 percent power increase,
- Installed a new Power Control Unit (PCU) requiring the power down of HST,
- Installed the Electronic Support Module (ESM) for NICMOS,
- Installed the NICMOS Cryocooler (NCC),
- Installed the NICMOS Cooling System Radiator,
- Replaced the new outer layer blanket on bay 6,
- Replaced a reaction wheel assembly, and
- Completed several minor get-ahead tasks on the HST structure.

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[18] NASA, STS-103 Space Shuttle Mission Report NSTS-37426, NASA Johnson Space Center, Houston, Tex., February 2000.

[19] NASA, STS-109 Space Shuttle Mission Report NSTS-37437, NASA Johnson Space Center, Houston, Tex., May 2002.

FINDING: In the case of every documented anomaly encountered during the conduct of extravehicular activities (EVAs) on all four HST missions, the onboard crew, in conjunction with its ground-based mission control team, worked around each anomaly and successfully completed every task planned for these missions.

HST SERVICING MISSION RISK

Mission risk depends on the availability of the shuttle and, once launched, the likelihood that the mission will be successfully accomplished (see also Chapter 7). Based on discussions with NASA PRA experts and using the expertise of committee members, the committee concludes that the shuttle will likely have an 80 to 90 percent probability of being available for an HST servicing mission by the time such a mission is scheduled to fly. Reasons why the shuttle would not be available include loss of vehicle on a previous flight, or a major anomaly that would ground the shuttle fleet for six months or more. The mission risk assessment by this committee is based on the accomplishments of previous shuttle missions involving satellite rescues utilizing EVAs, including the four successful shuttle missions to service HST as discussed in sections "Human Response to Unforeseen On-Orbit Contingencies" and "Space Shuttle Servicing Missions to the Hubble Space Telescope." In the nine flights considered, the EVA activities resulted in complete mission success in all but one instance, and that case was an unplanned EVA for the unexplained failure to activate on deployment of a SYNCOM IV-3 communications satellite.[20]

A more detailed discussion of the comparative mission risk between a human servicing mission and a robotic mission to HST is presented in Chapter 7.

FINDING: Space shuttle crews, in conjunction with their ground-based mission control teams, have consistently developed innovative procedures and techniques to bring about desired mission success when encountering unplanned for or unexpected contingencies on-orbit.

FINDING: The risk in the mission phase of a shuttle HST servicing mission is low.

[20] NASA, *First 100 Manned Space Missions*, NASA Kennedy Space Center Public Affairs Office, June 14, 1995, available online at http://science.ksc.nasa.gov/shuttle/missions/51-d/mission-51-d.html.

7
Benefit/Risk Assessment of Hubble Space Telescope Servicing Options

INTRODUCTION

A variety of risks and benefits are associated with on-orbit servicing of the Hubble Space Telescope (HST). There are risks to human safety, and several types of programmatic risks including not meeting cost requirements, not meeting schedule and not achieving mission objectives. As discussed in detail in Chapter 3, the benefits from HST servicing are in the continuation and enhancement of the science produced by the HST, the enhancement of NASA's image in the production of world-class science, and the educational value of inspiring the youth of the nation and the world in the pursuit of scientific careers. The assessment of a benefit/risk ratio for each alternative HST servicing option provides a measure of its efficacy.

Ideally, benefit/risk ratios are quantitative. In the case of HST servicing, NASA has not as yet completed a quantitative assessment of risk, which is expected later in 2004, nor is there a quantitative measure of the benefits to be achieved. Nevertheless, the committee was able to assess the benefit/risk for alternative servicing options, based on qualitative risk assessments, and qualitative consideration of the specific scientific benefits expected from the servicing options.

Benefit/risk comparisons were made for a human HST servicing mission and for a robotic mission. A glossary of risk terms relevant for the HST servicing situation is included in Table 7.1.

ASSESSMENT OF THE RISKS OF HUMAN AND ROBOTIC SERVICING

The risk to crew safety is discussed in Chapter 6, where it is concluded that the risk of a single shuttle mission to HST is essentially the same as the risk of a single mission to ISS. Given that finding, it remains to assess the cost, schedule and mission risks of the two types of Hubble servicing missions, human and robotic. The programmatic risks of meeting projected cost requirements and schedule are addressed throughout this report, and especially in Chapter 4 with respect to schedule. This chapter focuses on mission risk, which is the risk of not meeting the objectives of the servicing mission.

The preference of the committee would have been to rely on the review of risk assessments currently required by NASA's procedures for probabilistic risk assessment.[1] Unfortunately, primarily because NASA has only recently required full scope risk assessments, the risk assessment of primary interest to the committee is presently in the process of development. Therefore, it was unavailable to the committee. Furthermore, the risk assessment procedures for NASA programs and projects do not require risk assessments for non human-related missions. As a result of not having a risk assessment for either the shuttle or the robotic HST servicing missions for its review and analysis, the committee performed its own qualitative assessment of the risks of the two options based on briefings, meetings with NASA and contractor personnel, and selected references.

A top down qualitative approach was used to compare the risks. The focus of the assessment is on those on-orbit activities and events most relevant to the actual servicing operations that are common to both the human and robotic options. Since this section is focused on mission risk (or probability of success of a servicing mission), there is no assessment of risk during reentry for either type mission option. In particular, a representative success-oriented event sequence table was developed for each of the two missions (Tables 7.2 and 7.3). The individual mission events are assessed at a high level in

[1] NASA, 2004, Probabilistic Risk Assessment (PRA) Procedures for NASA Programs and Projects, NASA Procedural Requirements: 8705.5, NASA Office of Safety and Mission Assurance, Washington, D.C.

TABLE 7.1 Risk Glossary

Term	Definition
Risk	The combined answers to (1) What can go wrong? (2) How likely is it? And (3) What are the consequences?
Risk Assessment	The science of investigating the level of risk and the contributing factors associated with the risk of an event, process, or activity.
Risk Management	The process of making decisions and taking actions to control risk based on a systematic process of risk assessment.
Risk Benefit Analysis	The evaluation of the risks and benefits of an activity, system or program based on economic and performance considerations.
Programmatic Risk	The risk of an undesired impact on the cost, schedule and success of a program, project, or activity.
Mission Risk	The risk of not meeting the objectives of a particular mission
Health and Safety Risk	The risk of human health or safety consequences as a result of a particular event, process, or activity.
Risk Communication	An interactive process of exchange of information and opinions regarding risk, among individuals, groups, and institutions; often involving multiple messages about the nature of risk, and the expression of concerns, opinions, or reactions to risk messages.
De Minimis Risk	From the legal maxim " de minimis non curat lex" or " the law is not concerned with trifles."
Risk Perception	Risks as perceived by different groups of people. Frequently, risk perception is dependent on factors other than risks, such as unfamiliarity, acuteness, catastrophic image, etc.
Risk Characterization	A synthesis and summary of information about a hazard that addresses the needs and interests of decision makers and of interested and affected parties.

accordance with the "set of triplets" definition of risk (NASA;[2] Kaplan and Garrick[3]) as to 'what can go wrong'?, 'how likely is it?', and 'what are the consequences?' Generally, the first question is answered in the form of a structured set of scenarios. The end states of the scenarios are the consequences; the likelihoods of the scenarios individually and collectively are assessed based on the supporting evidence. While Tables 7.2 and 7.3 do not carry the process to completion, they do provide enough information to gain significant insight into the mission risks involved.

Definitions

Tables 7.2 and 7.3 were developed using the following terms and definitions.

[2] NASA, 2002,. Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners. Version 1.1., NASA Office of Safety and Mission Assurance, Washington, D.C.

[3] S. Kaplan and B.J. Garrick, 1981, On the quantitative definition of risk. *Risk Analysis* 1(1): 11-27.

Mission Phase

These are the major high-level phases that a servicing mission must complete to be successful. In the 'Pre-Launch' phase the entries in the tables deal more with cost and schedule risk than with mission success. The pre-launch phase is included more for completeness than as input to assessing the risk associated with mission success. The mission success risks are assessed for both mission options.

What Can Go Wrong?

Failures or undesired events are identified for each mission phase and sub-phase. The list of phases and events is not complete, but the failures and events identified are believed to be the most important ones for each mission, and they are representative of the types of threats that can prevent a successful mission. In a quantitative risk assessment many of the undesired events and failures that are identified in the tables would be analyzed in the context of scenarios, as either initiating events or as downstream events leading to some end state or consequence. In a quantitative risk assessment the mitigation of failures or undesired events (automated or based on crew actions) is taken into account in the determination of likelihoods and consequences. In the absence of detailed scenarios and failure data, judgments had to be made about the likelihoods and consequences of failures and undesired events, including the effect of risk mitigation features for each type of HST servicing option. The integration of undesired events and their possible mitigation was judgmental, based on briefings and documents presented to the committee.

Likelihood/Consequence

The likelihood of an event is classified into four broad categories, namely 'High', 'Medium', 'Low' and 'Extremely Low'. Likelihood is defined as the frequency per launch of a failure or undesired event, taking into consideration any mitigating features. The category 'High' was defined as 1 in 100 missions or greater, 'Medium' as between 1 in 100 to 1 in 300 missions, 'Low' as less than 1 in 300 missions, and "Extremely Low" (designated by a tilde (~)) as much less frequent than 1 in 300 missions.

A 'High' consequence event is defined as one that results in loss of mission, 'Medium' consequence implies loss of one mission element, and 'Low' consequence signifies a recoverable loss of capability.

Risk Significance

"Risk Significance' is a qualitative attempt to take into consideration all three of the risk factors: what can go wrong (scenarios), likelihoods (frequencies), and consequences (the end states of the scenarios). Risk Significance integrates and interprets likelihoods and consequences and accounts for the fact that catastrophic or even existential consequences do not always translate into high risk. For example, a giant asteroid striking the earth would have catastrophic or possibly even existential consequences, but its extremely low frequency of occurrence makes the risk of such an event low.

Uncertainty

In the absence of a quantitative expression of the risk, such as a frequency of occurrence parameter embedded in a probability distribution, a judgment of the uncertainty in 'Risk Significance' is based on an assessment of the quality of the supporting evidence. In particular, 'High' uncertainty implies considerable weakness in the evidence supporting the judgment on Risk Significance. It is possible for ‘uncertainty’ to dominate the risk.

Risk Tables

The entries in the event sequence tables are based on input from several sources. They include briefings received by the committee members, committee expertise on Hubble servicing missions and risk assessment, meetings with NASA risk assessment experts, and studies performed by NASA and others on risk and safety, including the Aerospace Corporation’s independent analysis of alternatives to servicing HST.[4,5]

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[4] Aerospace Corporation, 2004, “Hubble Space Telescope (HST) Servicing Analysis of Alternatives (AoA) Final Delivery Executive Summary,” presentation to the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope, August 3, 2004.

[5] NASA, 2004, “Hubble Space Telescope Robotic Servicing Mission Project,” Hubble Space Telescope Review Team Report, July 26, NASA Independent Program Assessment Office, Washington, D.C.

TABLE 7.2 Risk Significance of Shuttle Servicing Mission to the Hubble Space Telescope

Mission Phase	What Can Go Wrong?	Likelihood/ Consequence	Risk Significance	Uncertainty	Comments
Pre-Launch	Previous Loss of Vehicle or Crew	High/High	High	Medium	Events occurring during pre-launch are more related to programmatic risk than to specific mission risk. Noted for completeness.
Complete Launch Countdown	Previous Anomaly (major problem)	Medium/Medium	Medium	Medium	
Launch and Ascent:	Loss of Vehicle or Crew	High/High	High	Medium	
Launch	Abort/Unable to Effect Rendezvous	Medium/High	Medium	Medium	
Successful Main Engine Cut-Off					
Orbit:	Orbital Debris Penetration of Vehicle (before servicing)	Low/High	Low	Medium	
Orbit Insertion					
Rendezvous	Abort Mission (systems, performance, etc.)	High/High	High	Low	
	Abort Rendezvous	Low/High	Low	Low	
	Radar Loss	High/Low	Low	Low	
Capture, Grapple, Mating	RMS Failure	Low/High	Low	Low	Mitigation alternatives available.
	RMS Degradation	Medium/Low	Low	Low	Workarounds available for degraded performance.
	Tip-Off Rates Generated	Low/Low	Low	Low	Workarounds available.
	HST Tumbling/ Attitude Control Loss	~/High	Low	Low	Very unlikely to occur.
	FSS Latch Failure	~/Low	Low	Low	EVA required.
	Failure to Make Electrical Power Connection	~/Medium	Low	Low	Workarounds available. Redundant connectors.
	Collision with Hubble	Low/High	Low	Low	Would significantly affect HST continuation.

TABLE 7.2 Continued

Mission Phase	What Can Go Wrong?	Likelihood/ Consequence	Risk Significance	Uncertainty	Comments
EVA/ Servicing (5 EVAs):	Orbital Debris Penetration of EMU	Low/High	Low	Low	
	Loss of Space to Ground COMM	Low/Low	Low	Low	
	Inadequate Time for Operations/ Repair (failure to complete)	Low/Low	Low	Medium	Assumes partial mission completion.
	EMU Failure	Medium/Low	Low	Low	Early termination of EVA. Extra suits and contingency time.
Effect Access to HST Instrument Compartments	Latch Failure	High/Medium	Low	Low	Latch replacement is routine. Assumes partial loss of mission.
	Unexpected Obstruction	Low/Medium	Low	Low	Easy to recover. Assumes partial loss of mission.
Removal of Hardware from Transport Locations	Unable to Remove Hardware	Low/Medium	Low	Low	Assumes partial loss of mission.
	Carrier Door Does Not Open	Low/Low	Low	Medium	Assumes partial loss of mission.
Removal and Installation of Hardware for Each of 5 EVAs	Incorrect Cable Length	Low/Low	Low	Low	Assumes partial loss of mission.
	Bent Pin	Medium/Low	Low	Low	Some repair capability exists. Assumes partial loss of mission.
	Inability to De-Mate/Mate Connector	Low/Med	Low	Low	Assumes partial loss of mission.
	Tool Failure	Low/Low	Low	Low	Workarounds/backup tools available.
	RMS Joint Failure	Low/High	Low	Low	Some workarounds for limited tasks.
	RMS Fail to Release	Low/High	Low	Low	Jettison of arm would significantly affect HST continuation.
	RMS Fail to Grapple	Low/High	Low	Low	
	Cable Failure from Excessive Force	Low/Medium	Low	Medium	Possible EVA-induced loads. Crews specifically train for this.

TABLE 7.2 Continued

Mission Phase	What Can Go Wrong?	Likelihood/ Consequence	Risk Significance	Uncertainty	Comments
Removal and Installation of Hardware for Each of 5 EVAs, continued	Loss of Tool (includes tether failure)	Low/Medium	Low	Low	Recovery of tool or collision avoidance maneuver provides mitigation. Optics bay is highest risk.
	Misalignment/ Binding of Instrument during Removal from HST	Low/Medium	Low	Medium	
	Misalignment/ Binding of Instrument during Insertion into HST	Medium/Medium	Medium	Medium	Does not consider getting instrument stuck, preventing safe closeout.
	Exceeding of Thermal Limits/Attitude Constraints	Low/Low	Low	Low	
	Contamination of Hubble Arrays, Control Surfaces, etc.	Low/High	Low	Low	
Close and Secure all Panels/Doors	Latch Failure	High/Medium	Low	Medium	Assumes partial loss of mission.
	Panel Deformation	Low/High	Low	Medium	Inability to close axial doors—severe consequence.
Re-Boost Hubble[1]	Inadequate Propellant for Re-Boost	Low/Medium	Low	Low	Carefully planned for—requires orbiter propulsion system failure.
Re-Deploy Hubble[2]	RMS Failure	Low/Low	Low	Low	
	Re-Contact with Hubble	Low/High	Low	Low	Would significantly affect HST continuation.

[1] Not considered for robotic servicing mission due to assumption that re-boost will not be planned.
[2] Not required for a robotic servicing mission.

TABLE 7.3 Risk Significance of Robotic Servicing Mission to the Hubble Space Telescope

Mission Phase	What Can Go Wrong?	Likelihood/ Consequence	Risk Significance	Uncertainty	Comments
Pre-Launch	Previous Loss of Vehicle (Expendable launch vehicle (ELV) is less reliable than shuttle)	High/High	High	High	Return to flight can be months to years even for ELV.
	Previous Anomaly (Orbital Express/XSS-11)	Medium/Medium	Medium	High	Late in mission development process.
	Hardware Development Problems	High/High	High	High	Proximity operations sensor technology immature.
	Multi-Vehicle Systems Engineering Ground Test Failures	High/Medium	Medium	Medium	
	Ground Test Software Not Ready	Medium/Medium	Medium	Medium	Systems architecture currently immature.
	Flight Software Not Ready	High/High	High	High	Systems architecture currently immature.
	Operator Interfaces Not Developed	Low/Medium	Medium	Medium	
	Training and Simulation Not Ready	Low/Medium	Medium	Medium	
	Resources Not Available When Needed	High/High	High	High	

TABLE 7.3 Continued

Mission Phase	What Can Go Wrong?	Likelihood/ Consequence	Risk Significance	Uncertainty	Comments
Launch and Ascent:	Loss of Vehicle	Low/High	Low	Medium	
	Abort/Unable to Effect Rendezvous	Low/High	Low	Medium	
Rendezvous	Failure to Rendezvous	Low/High	Medium	Medium	
	Proximity Operations/Rate Matching Failure	High/High	High	High	
Capture, Grapple, Mating	Robotic System Checkout Failure	Low/High	Medium	Medium	
	Failure to Berth Deorbit Module	High/High	High	High	
	Failure to Ungrapple HST/Deploy Dexterous Robot	Medium/High	Medium	High	
	Failure to Demate/Mate Power Connectors	Medium/High	Medium	Medium	
	Failure to Open Access Doors and Keep Them Open	Low/Medium	Low	Low	
Effect Access to HST Instrument Compartment	Failure to Tether Cables out of the Way	Low/Medium	Medium	Medium	
	Connector Cable Failure (bent pin)	Low/Medium	Low	Low	
Removal and Installation of Hardware	Loss of Control of Connector	Low/Low	Low	Low	
	Dexterous Robotic System Arm Failure	Medium/High	High	High	
	Vision System Camera Fails	Medium/Medium	Medium	Low	
	Failure of Robotic System to Grapple/Release Tool	Medium/Medium	Medium	Medium	
	Failure of Tool	Medium/Medium	Medium	Low	Two examples of tool failures on two of four HST servicing missions.
	Loss of Servicing Tool	Medium/Low	Low	Low	

TABLE 7.3 Continued

Mission Phase	What Can Go Wrong?	Likelihood/ Consequence	Risk Significance	Uncertainty	Comments
	Misalignment/ Binding of Instrument During Removal/ Installation	Low/High	Medium	Low	Several occurrences on HST servicing missions.
	Failure of Force Feedback System in Dextrous Robotic System	Medium/High	Medium	Medium	Could result in instrument damage.
	Exceedance of Attitude/Thermal Limitations during Instrument Changeout	Low/Medium	Low	Medium	
	Loss of Control of Instrument During Changeout/ Impact/ Complete Loss of Instrument	Low/Medium	Low	Medium	
	Software Incompatibility/ Failure in Integrated Robotic System	Low/Low	Low	Low	
	Failure to Stow Removed Instrument (no ability to jettison)	Low/High	Low	Medium	No jettison, no separation maneuver. Significant HST impact.
	Contamination of Hubble Arrays, Control Surfaces, etc.	Medium/High	Medium	Medium	
Close and Secure All Panels/Doors	Latch Failure	High/Medium	High	Medium	Assumes partial loss of mission
	Panel Deformation	Low/High	High	Medium	Inability to close axial doors—severe consequences
Deorbit Preparation:[1]	Inability to Separate Deorbit Module from Equipment Module	Low/Medium	Low	Medium	
	Misalignment of Deorbit Thrust Vector due to Incorrect Attachment of Deorbit Module	Low/Medium	Low	Medium	

[1] Not considered for human servicing mission due to assumption that SM-4 will not include installation of deorbit module.

The entries in Tables 7.2 and 7.3 are based on current NASA plans and schedules. A change of plans would result in a different assessment of a particular entry or entries, or might eliminate one of the entries entirely in the case of a de-scoped mission. A number of factors could impact the assessed risk(s), possibly favorably in some cases. Examples of such factors are de-scoping the servicing mission, extending the time for servicing by one year, performing on-orbit technology demonstrations (e.g., orbital express), and/or an aggressive program of robotic systems development and integration.

Table 7.2 addresses some of the risk issues of the human servicing option for Hubble. The previous highly successful servicing missions to HST have contributed significantly to a high overall confidence in mission success. For those cases where the likelihood or consequence is rated Medium or High, experience indicates that there are a number of options for mitigating their risk significance. Examples of failures and undesired events during past human servicing, where human presence was vital to risk mitigation include remote manipulator system (RMS) failure or degradation, inability to remove hardware, bent pins on connectors, misalignment or binding of instruments during emplacement, and loss of tools. (See Chapter 6 for a more comprehensive discussion of previous successes).

Experience and analysis also indicate that several high consequence failures or undesired events are of low 'Risk Significance' because of their very low likelihood of occurrence. Examples are orbital debris penetration, radar loss, loss of attitude control, loss of electrical power, and on-orbit catastrophic events. The on-orbit operation of highest mission risk for the human servicing mission is the possibility of having to abort the mission due to system problems.

The experience base for human servicing of HST provides strong supporting evidence of the feasibility and reliability of the rendezvous and servicing operations. (See Chapter 6 for additional supporting evidence). The preparation of the HST for cooperative robotic capture to attach a de-orbit module is included in the scenario sequence of Table 7.2 for completeness of the discussion. The shuttle servicing mission is ideally suited to the preparation of the HST for later robotic de-orbit (see "Benefit/Risk Assessment for Servicing Options" below and Chapter 8 for further discussion of the de-orbit issue).

Table 7.3 addresses some of the risk issues associated with the robotic servicing mission to Hubble. The overarching risk is the uncertainty in the reliability of the docking, servicing, and de-mating operations in the absence of any in-flight experience. Among the greatest threats to a successful robotic servicing mission are navigational problems in proximity (within 5 to 50 meters) of the HST, possible failure to grapple and dock with the HST, failure of the dexterous robotic system during servicing, limitations of robotic alternatives in dealing with unanticipated events and failures, failure to berth the de-orbit module, and failure to de-mate. Among the most serious failures would be that of the dexterous robotic arm. Such failures would result in total or partial failure of the mission (see Chapter 5 for more detailed discussions).

The analyses presented in Tables 7.2 and 7.3 indicate that the proposed HST robotic servicing mission involves a level of complexity that is inconsistent with the current robotic development schedule and would require an unprecedented reduction in the time required for system development, compared to space missions of similar complexity (see also Chapter 4). The likelihood of successful development of the HST robotic servicing mission within the baseline 36-month schedule is deemed to be remote. The independent study performed by the Aerospace Corporation indicates that the most probable estimate is that 65 months are required for development of a combined servicing and de-orbiting mission; 26 months more than the NASA 39-month schedule. The Aerospace Corporation report indicates a "high failure risk due to the unprecedented mission and unproven technologies (~50 percent probability of failure . . .)." Extending the robotics schedule to allow for a more reasonable development interval is not possible because the robotic mission does not "reset the avionics failure clock" the way a shuttle mission can, as explained in Chapter 4. As discussed in detail in Chapter 4, this leads to a high probability that the spacecraft will fail due to some unforeseen avionics failure before the end of the 3 to 5 year post-servicing mission, if robotic repair is not prompt.

Conclusions Regarding Risk for Servicing Options

Tables 7.2 and 7.3 show the risk significance of the various failure scenarios for human and robotic HST servicing options respectively. A comparison of the analyses in these two tables indicates that there is strong evidence of lower mission risk for the human servicing option. This is based on the experience base for the human servicing of the HST, including the demonstrated capability of humans to diagnose unanticipated failures and take corrective action (see Chapter 6).

There remains high uncertainty about the range of corrective actions which can be performed robotically, as is discussed in Chapter 5. In addition, there is strong supporting evidence of high mission risk in the successful system development and testing of the robotic servicing option in the short time available.

FINDING: Although a quantitative mission risk assessment does not exist for either a human or a robotic servicing mission to the Hubble Space Telescope, the committee's qualitative evaluations lead it to conclude that the human servicing mission poses a low risk to mission success. Conversely, the robotic mission risk is high, considering the short time frame available for system development and testing, and the uncertainty concerning robotic performance.

BENEFIT/RISK ASSESSMENT FOR SERVICING OPTIONS

Despite the absence of quantitative analyses of the risks and benefits from the two types of HST servicing missions, the committee has determined that a human mission poses low mission risk, whereas a robotic mission poses high mission risk. The benefits from either mission are comparably high (if the robotic mission performs all its intended activities), especially in terms of the quantity and quality of science to be derived from the continuation of the HST mission, and the enhancement of HST performance. A quantitative benefit/risk assessment cannot be made for either mission. However, the committee can conclude that the benefit/risk ratio for the human mission is high, and the benefit/risk ratio for the robotic mission is low. This conclusion follows from:

1. The enormous benefits to science, including enhanced understanding of the physical universe, as articulated in Chapter 3.
2. The conclusion in Chapter 6 that the safety risk for a single mission to the International Space Station is comparable to the safety risk for a mission to the Hubble Space Telescope.
3. The analysis presented in this chapter on the mission risk for the two options.

8
Conclusions and Recommendations

The Hubble Space Telescope (HST) provides a host of unique and important capabilities for astronomical research, many of which will not be replaced by any existing or currently planned astronomy facility in space or on Earth. Hubble's continuing and extraordinary impact on human understanding of the physical universe has been internationally recognized by scientists and the public alike. In recognition of the importance of this science facility to human knowledge, a fifth shuttle servicing mission (SM-4) was in the planning stage prior to the Columbia accident in 2003.

The SM-4 mission was in planning to install two new instruments and to perform a number of upgrades to avionics systems. These upgrades are necessary because of the predictable decline in HST component performance over time. This decline in system reliability requires a timely and successful servicing mission in order to minimize further degradation and avoid a significant gap in the return of science data.

The need for timely servicing of Hubble imposes difficult requirements on the development of a robotic servicing mission. The very aggressive schedule, the complexity of the mission design, the current low level of technology maturity, and the inability of a robotics mission to respond to unforeseen failures that may well occur on Hubble between now and the mission make it highly unlikely that the science life of HST will be extended through robotic servicing.

A shuttle servicing mission is the best option for extending the life of Hubble and preparing the observatory for eventual robotic de-orbit; such a mission is highly likely to succeed. The committee believes that this servicing mission could occur as early as the seventh shuttle mission following return to flight, at which point critical shuttle missions required for maintaining the ISS will have been accomplished.

The committee finds that the difference between the risk faced by the crew of a single shuttle mission to the ISS—already accepted by NASA and the nation—and the risk faced by the crew of a shuttle mission to HST, is very small. Given the intrinsic value of a serviced Hubble, and the high likelihood of success for a shuttle servicing mission, the committee judges that such a mission is worth the risk.

RECOMMENDATIONS

1. The committee reiterates the recommendation from its interim report that NASA should commit to a servicing mission to the Hubble Space Telescope that accomplishes the objectives of the originally planned SM-4 mission.
2. The committee recommends that NASA pursue a shuttle servicing mission to HST that would accomplish the above stated goal. Strong consideration should be given to flying this mission as early as possible after return to flight.
3. A robotic mission approach should be pursued solely to de-orbit Hubble after the period of extended science operations enabled by a shuttle astronaut servicing mission, thus allowing time for the appropriate development of the necessary robotic technology.

Appendixes

A
Statement of Task

The committee will conduct an independent assessment of options for extending the life of the Hubble Space Telescope. The study will address the following tasks:

1. Assess the viability of a space shuttle servicing mission that will satisfy all recommendations from the CAIB, as well as ones identified by NASA's own Return-to-Flight activities. In making this assessment, compare the risks of a space shuttle servicing mission to HST with the risks of a shuttle mission to the ISS and, where there are differences, describe the extent to which those differences are significant. Estimate to the extent possible the time and resources needed to overcome any unique technical or safety issues associated with HST servicing that are required to meet the CAIB recommendations, as well as those from the Stafford-Covey team.
2. Survey other available engineering options, including both on-orbit robotic intervention and optimization of ground operations, that could extend the HST lifetime.
3. Assess the response of the spacecraft to likely component failures and the resulting impact on servicing feasibility, lost science, and the ability to safely dispose of HST at the end of its service life.
4. Based upon the results of the tasks above, provide a benefit/risk assessment of whether extension of HST service life, via (a) a shuttle serving mission if one is deemed viable under task #1 and/or (b) a robotic servicing mission if one is deemed viable under task #2, is worth the risks involved. The assessment should include consideration of the scientific gains from different options considered and of the scientific value of HST in the larger context of ground and space-based astronomy and science more broadly. Special attention should be paid to the practical implications of the limited time available for meaningful intervention robotically or via the shuttle.

The committee is not expected to make either organizational or budgetary recommendations, but it may need to consider cost as a factor in weighing the relative benefits of alternative approaches.

The committee will investigate the possibility of providing an interim report to NASA that addresses a portion of the items in the task statement in advance of delivering a full final report if such an approach is deemed feasible and able to provide early, credible answers to the questions being considered.

B
Briefings to the Committee

JUNE 1, 2004

Congressional Perspectives on Servicing Options, NRC Study
David Goldston, House Science Committee Majority Chief of Staff

NASA's Expectations for NRC Study and Code S's Readiness for Servicing Options
Ed Weiler, NASA Associate Administrator, Space Science

NASA's Readiness for Return to Flight, Status of ISS, and Human Servicing Considerations
Bill Readdy, NASA Associate Administrator, Space Flight

Findings and Recommendations of the CAIB
Admiral Hal Gehman, Chair, CAIB

Report on 'Second Interim Report' (May 19, 2004) by Return to Flight Task Group
Forrest McCartney, Member, RtF Task Group

Findings and Recommendations of the HST-JWST Transition Team
John Bahcall, Chair, Transition Team

JUNE 2, 2004

Status of Hubble Spacecraft
Ed Ruitberg, HST Deputy Program Manager, GSFC
Keith Kalinowski, HST Systems Manager

Hubble Ground Operations and Science Impact
Rodger Doxsey, Space Telescope Science Institute

Shuttle and Mission Operations: Requirements for Human Servicing Mission
Randall Adams, Deputy Manager of Flight Operations and Integration, JSC
Wayne Hale, Deputy Manager of Shuttle Program, JSC

Robotic Servicing Options
Frank Cepollina, Deputy Associate Director, HST Development Project, GSFC
Mike Weiss, HST Deputy Program Manager/Technical, GSFC

JUNE 22, 2004

HST in the Larger Scientific Context
John Huchra, Senior Astronomer and Professor, Harvard-Smithsonian Center for Astrophysics

Ground-Based Telescope Capabilities
Claire Max, Associate Director, Center for Adaptive Optics

Future Science Expected from HST
Steve Beckwith, Director, Space Telescope Science Institute

HQ Perspective on Servicing Options
Sean O'Keefe, NASA Administrator

Cost and Budget Projections for JWST and HST
Rick Howard, Associate Director for Astronomy and Physics, NASA HQ

Continuation of Discussion of HST Health and Status
Keith Kalinowski, HST Systems Manager, GSFC

JUNE 23, 2004

State-of-the-Art in Rendezvous, Formation Flying, and Capture
Darryl Sargent, Director of Space Systems, Draper Laboratory

Code Q Risk Assessment
Bryan O'Connor, NASA Associate Administrator, Office of Safety and Mission Assurance

Shuttle Program Risk Analysis, Baseline requirements
Robert Lightfoot, Assistant Associate Administrator, Space Shuttle Program

Results of the Robotics RFI
Mike Weiss, HST Deputy Program Manager/Technical, GSFC

Video of Mission Scenario
Jill Holz/James Corbo

Cost and Budget Estimates
Richard King

Technical Approach for Automated Rendezvous and Capture
R. Burns

Robot/Grapple Arm: Technical and Schedule Risk
J. Lymer

HST Robotic Servicing Risks and Risk Mitigation Plans
James Corbo/Mark Turczyn

JULY 12, 2004

Robotic Servicing: Budget Plans, Applications to Exploration
Craig Steidle, NASA Associate Administrator, Exploration Systems
Steve Isakowitz, NASA Comptroller

Alternatives to Servicing HST (Aerospace Corporation Study)
Mike Moore, HST Program Executive, NASA HQ

JULY 13, 2004

HST Lifetimes: Fine Guidance Sensors, Reaction Wheels
Keith Kalinowski, HST Systems Manager

Update on HST Batteries
Keith Kalinowski, HST Systems Manager
Steven Gentz, NESC HST Battery Panel Chair

Orbital Express
James Shoemaker, DARPA Program Manager, Orbital Express

AUGUST 23, 2004

Status of NASA's Robotic Servicing Evaluation
Al Diaz, Associate Administrator, Science Mission Directorate

AUGUST 24, 2004

Perspectives on Hubble Servicing
Bruce McCandless II

Hubble Servicing Options Report Briefing
Aerospace Corporation representatives

NASA Origins Probe Studies
Jennifer Wiseman, Hubble Program Scientist

C
Interim Report

July 13, 2004

The Honorable Sean O'Keefe
Administrator
National Aeronautics and Space Administration
Washington, DC 20546-0001

Dear Mr. O'Keefe:

At the request of the National Aeronautics and Space Administration, the National Research Council recently established the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope.[1] The committee's statement of task charges it to assess the viability of a shuttle servicing mission, evaluate robotic and ground operations to extend the life of the telescope as a valuable scientific tool, assess telescope component failures and their impact, and provide an overall risk-benefit assessment of servicing options.[2] The statement of task includes the possibility of transmitting an interim report to NASA prior to the submission of a final report.

The committee thanks you very much for your generous allocation of time in meeting with it on June 22, 2004. The information that you conveyed on the decision-making process that you and NASA followed when arriving at the Hubble-related decisions in January and in March 2004 was very important for us to hear directly from you. The additional information that you provided on NASA activities related to the shuttle return-to-flight program and robotic engineering in the broader context of long-term human space exploration was very useful, as was the extensive question-and-answer dialog that you enthusiastically engaged in with the committee.

Because you and your NASA colleagues have made clear to the committee that there is some urgency in issuing any recommendations related to Hubble, we are providing you with this interim report.[3] It offers three principal findings and recommendations. These are based on the committee's collective knowledge as well as input from other experts, both internal and external to NASA. This interim report does not address any one request in the statement of task in its entirety, but rather touches on aspects of task components 1, 2, and 4. Here the committee considers the degree of importance that a Hubble servicing mission would have for science, as well as some of the key factors involved in selecting a servicing mission option. Its aim is to provide useful guidance to NASA that can be utilized during the time that the committee (as well as NASA) continues to investigate the servicing options in greater detail. The work of the committee will continue during the coming weeks, and we expect to finish drafting a final report by late summer or early fall. The final report will address in detail all four of the requests in the study's statement of task.

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[1] The committee roster is provided in enclosure A. Additional background material on the motivation for the study can be found in enclosure B.

[2] See the statement of task in enclosure B.

[3] Information about the independent review of the committee's report under the supervision of the NRC's Report Review Committee is provided in enclosure C.

Importance of a Hubble Servicing Mission

The Hubble Space Telescope (HST) is arguably the most important telescope in history. Much of Hubble's extraordinary impact was foreseen when the telescope was being planned. It was predicted, for example, that the space telescope would reveal massive black holes at the centers of nearby galaxies, measure the size and age of the observable universe, probe far enough back in time to capture galaxies soon after their formation, and provide crucial keys to the evolution of chemical elements within stars.

All of these predicted advances have been realized, but the list of unforeseen Hubble accomplishments may prove even greater. Hubble did discover "adolescent" galaxies, but it also saw much farther back in time to capture galaxies on the very threshold of formation. Einstein's theory of general relativity was bolstered by the detection of myriad gravitational lenses, each one probing the mysterious dark matter that pervades galaxies and clusters of galaxies. Gamma-ray bursts had puzzled astronomers for more than 20 years; in concert with ground and x-ray telescopes, Hubble placed them near the edge of the visible universe and established them as the universe's brightest beacons, outshining whole galaxies for brief moments. Perhaps most spectacularly, Hubble confirmed and strengthened preliminary evidence from other telescopes for the existence of "dark energy," a new constituent of the universe that generates a repulsive gravity whose effect is to drive galaxies apart faster over time. The resulting acceleration of universal expansion is a new development in physics, possibly as important as the landmark discoveries of quantum mechanics and general relativity near the beginning of the 20th century.

Closer to home, Hubble has zeroed in on our own cosmic past by uncovering virtual carbon copies of how the Sun and solar system formed. Dozens of protoplanetary disks have been found encircling young stars in nearby star-forming regions of the Milky Way. The sizes and densities of these disks show how surplus dust and gas collect near infant stars to form the raw material of planets. Dozens of large, Jupiter-like planets have been discovered, initially by other telescopes but recently by Hubble using a new and more precise method. Measuring the tiny drop in light as a planet transits the disk of its parent star, the new technique could lead to a method for discovering Earth-like planets—a discovery with tremendous long-term implications for the human race.

Riveting as they are, these scientific returns from Hubble are far from their natural end. With its present instruments the telescope could continue probing star formation and evolution, gathering more data on planetary systems, revealing planetary and cometary phenomena in our own solar system, and exploring the nature of the universe at much earlier times. However, two new instruments, already built for NASA's next planned servicing mission (SM-4), would amplify the telescope's capabilities by allowing qualitatively new observations in two underexploited spectral regions. Such rejuvenation via new instruments has occurred after every Hubble servicing mission, and the next one promises to be no different. Wide Field Camera-3 (WFC3) would increase Hubble's discovery efficiency[4] for ultraviolet and near-infrared imaging by factors of 10 to 30. The UV channel coupled with the camera's wide field of view will image the final assembly of galaxies still taking place in the universe. The near-infrared channel of WFC3 favors discovery of the very youngest galaxies, whose light is maximally red-shifted. The available UV, visible, and near-IR channels will combine to give a sweeping, panchromatic view of objects as diverse as star clusters, interstellar gas clouds, galaxies, and planets in our own solar system.

The second new instrument, the Cosmic Origins Spectrograph (COS), will increase Hubble's observing speed for typical medium-resolution ultraviolet spectroscopy by at least a factor of 10 to 30, and in some cases by nearly two orders of magnitude. Ultraviolet spectra carry vital clues to the nature of both the oldest and the youngest stars, yet UV rays are totally invisible from Earth's surface. COS will fill important gaps in our understanding of the birth and death of stars in nearby galaxies. Even more

[4] Throughput multiplied by the area of the field of view.

impressive, COS will use the light of distant quasars to spotlight hitherto undetectable clouds of dispersed gas between nearby galaxies, thereby mapping in unprecedented detail the properties of the so-called "cosmic web."

FINDING. Compelling scientific returns will result from a servicing mission to the Hubble Space Telescope that accomplishes the scientific objectives of the originally planned NASA servicing mission SM-4.

RECOMMENDATION. The committee urges that NASA commit to a servicing mission to the Hubble Space Telescope that accomplishes the objectives of the originally planned SM-4 mission, including both the replacement of the present instruments with the two instruments already developed for flight—the Wide Field Camera-3 and the Cosmic Origins Spectrograph—and the engineering objectives, such as gyroscope and battery replacements. Such a servicing mission would extend the life of this unique telescope and maximize its productivity.

Other potential options to extend the useful life of Hubble—for example, by servicing components such as batteries and gyroscopes but without replacing instruments—will be studied by the committee as part of its charge. However, such a reduced level of servicing has not been featured in the repair strategies that the committee has heard about to date. The scientific impacts of reduced levels of servicing below that envisioned in SM-4 will be considered in the committee's final report.

Servicing Mission Options

A wide range of factors must be considered when assessing the risk and effectiveness of HST servicing and deorbiting options. These options range from robotically attaching a deorbit module to Hubble to performing a mission (human or robotic) that replaces both scientific instruments and also services or repairs a number of engineering components. You discussed many of these options with us on June 22. One essential task is to enable the ultimate safe deorbiting of the spacecraft so that humans on Earth will not be at risk during its reentry. The present plan is to launch and robotically attach a deorbit module to the telescope around the year 2013.[5] Consistent with this plan, NASA issued a Request for Proposals (RFP) on June 1, 2004, for a Hubble disposal vehicle.[6]

Another risk concerns robotic servicing and possible replacement of telescope instruments. You told the committee that a robotic mission "will be really tough." NASA has proposed that a deorbit module might be attached to the spacecraft at the time of robotic servicing, although the recently issued RFP does not specifically require either servicing or instrument replacement.[7]

The committee has been given detailed information on the plans for robotic servicing currently under consideration by NASA at its Goddard Space Flight Center. A subgroup of the committee visited Goddard and examined the current activities. The robotic servicing development effort at Goddard was officially initiated in 2004 and is a very recent undertaking. While considerable advances have been made in just a few months, there has been little time for NASA to evaluate and understand the technical and schedule limitations of robotic servicing.

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[5] This is the earliest date at which Hubble would be expected to reenter the atmosphere without intervention.

[6] The RFP is available online at http://www2.eps.gov/spg/NASA/GSFC/OPDC20220/HST%2DDM%2D0002%2DGDJ/listing.html.

[7] The RFP requires only submissions for a vehicle to provide end-of-life controlled reentry or other safe disposal of the HST; the RFP invites but does not require that submissions include life extension or servicing capabilities.

The committee was gratified by your assurance that the robotic efforts will be adequately supported by the required resources in a timely manner. During the next year the robotic servicing mission project will have to achieve key milestones (including a critical design review in the summer of 2005) that will clarify the feasibility of a robotic servicing mission. Substantial resources will be required in Fiscal Year 2005 to accomplish this.

The committee finds the proposed robotic mission to be highly complex due to the inherent difficulties with supervised autonomy in the presence of time delays; the integration of vision and force feedback in six-degree-of-freedom assembly and disassembly tasks with high-degree-of-freedom, dexterous manipulators; and the coordinated control of the high-inertia HRV[8] with a long-reach robotic arm grappling with a high-inertia payload. Robotic emplacement of a deorbit module and replacement of instruments and subsystems on Hubble will require a rendezvous with a non-cooperative vehicle[9] together with a human in a telerobotic loop that has a substantial (on the order of 2-second) time delay.

The committee was informed about several current U.S. and foreign space programs that involve various concepts for robotic spacecraft rendezvous, capture, and servicing. Related U.S. experimental programs are currently scheduled for November 2004 (U.S. Air Force) and September 2006 (DARPA[10]). The committee has been informed that NASA is participating in some aspects of the DARPA program but this does not yet include a commitment to Hubble robotics servicing mission demonstrations. To the best of the committee's current understanding, difficult challenges of the Hubble robotic scenario (such as the time delay and a non-cooperative target) are not currently covered explicitly in either the Air Force or the DARPA programs. Based on information provided to the committee and the knowledge of members who have deep experience with shuttle flights and spacecraft servicing, the committee believes that the proposed robotic mission to Hubble will essentially be an experimental test program that is expected to accomplish specific programmatic objectives at the same time.

FINDING. The proposed Hubble robotic servicing mission involves a level of complexity, sophistication, and technology maturity that requires significant development, integration, and demonstration to reach flight readiness.

RECOMMENDATION. As an early step, NASA should begin immediately to take an active partnership role that includes HST-related demonstrations in the robotics space experiments that are now under way in other agencies in order to ensure that the returns from these experiments can be beneficial to a potential robotic Hubble servicing mission.

The four HST shuttle servicing missions already completed have demonstrated that crew servicing and instrument replacement can be highly successful. Of course, there is risk to the astronaut crew in any human flight mission. As you informed the committee, some 25 to 30 additional shuttle missions are planned to complete the International Space Station (ISS). Based on its current assessment of the conclusions and recommendations contained in the Columbia Accident Investigation Board (CAIB) report[11] and the Stafford-Covey reports (latest dated May 19, 2004),[12] the committee concludes that a

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[8] Hubble Robotic Vehicle.

[9] A non-cooperative vehicle is a vehicle that is not equipped with transponders or active sensors, meaning that it cannot respond to electronic interrogation from other spacecraft or emit signals enabling its identification or localization.

[10] Defense Advanced Research Projects Agency.

[11] NASA, *Columbia Accident Investigation Board Report, Volume 1,* August 2003, U.S. Government Printing Office, Washington, D.C.

[12] Return to Flight Task Group Interim Report, January 20, 2004, and Return to Flight Task Group Second Interim Report, May 19, 2004.

shuttle flight to the HST is not precluded by or inconsistent with the recommendations from these two NASA advisory groups.

The committee finds that the CAIB report makes clear distinctions between missions to the ISS and non-ISS missions. The CAIB report notes that the degree of difficulty is somewhat greater when conducting a non-ISS shuttle mission.[13] This is partially due to the fact that a non-ISS mission such as one to Hubble would not have as long a "safe haven" opportunity as would a mission docking with the space station. The shuttle repair capabilities at a non-ISS location would also be less robust than at the ISS itself. Even so, the CAIB report does not prescribe operational constraints on how to conduct a non-ISS mission, but rather only general risk mitigation steps that should be followed. The CAIB consciously accepted lower risk mitigation efforts for non-ISS missions (such as a mission to Hubble).[14]

The committee was cognizant and most appreciative of your extensive discussions with us related to the ownership that you, and NASA, have for the shuttle return-to-flight and for astronaut safety in the nation's civil space program. You stressed that total elimination of risk in crewed spaceflight is "impossible" and that you and NASA are "not risk averse." From information it has received, including the risk information to date, the committee concludes that there would be little additional investment in time and resources required over the next year for NASA to keep open an option for a human servicing mission to Hubble.

According to briefings received by the committee, the risk assessments for viable Hubble servicing alternatives, both human and robotic, have not yet been completed or reported by NASA. The Hubble project office is currently investigating risks associated with robotic mission scenarios. Additionally, the committee was told that probabilistic risk assessment results for shuttle flights should be available in the fall or winter of this year. Such a study will be important in improving the comparisons between the risks of human flights to the ISS and to Hubble.

FINDING. Because of inherent uncertainties in the early stages of development of a robotic mission to the Hubble Space Telescope, as well as the uncertain current status of the shuttle return-to-flight program, the key technical decision points for committing to a specific service scenario are at least a year in the future.

RECOMMENDATION. At the same time that NASA is vigorously pursuing development of robotic servicing capabilities, and until the agency has completed a more comprehensive examination of the engineering and technology issues, including risk assessments related to both robotic and human servicing options, NASA should take no actions that would preclude a space shuttle servicing mission to the Hubble Space Telescope.

We would be pleased to brief you and your staff regarding the views expressed in this letter. We remain committed to completing our final report in an expedited fashion.

Sincerely,

Louis J. Lanzerotti, *Chair*
Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope

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[13] CAIB Report Recommendation R6.4-1, p. 174.
[14] Ibid.

Enclosures:

A Membership roster of the Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope (as of July 2004)
B Project Overview
C Acknowledgement of Reviewers

cc: Edward J. Weiler, Associate Administrator, Office of Space Science, NASA
Craig E. Steidle, Associate Administrator, Office of Exploration Systems, NASA
William F. Readdy, Associate Administrator, Office of Space Flight, NASA
Lennard A. Fisk, Chair, Space Studies Board
William W. Hoover, Chair, Aeronautics and Space Engineering Board
Joseph K. Alexander, Director, Space Studies Board
George Levin, Director, Aeronautics and Space Engineering Board

Enclosure A

Committee on the Assessment of Options for Extending the Life of the Hubble Space Telescope

LOUIS J. LANZEROTTI, *Chair*, Consultant, Bell Laboratories, Lucent Technologies, and New Jersey Institute of Technology, Murray Hill, New Jersey
STEVEN J. BATTEL, Battel Engineering, Scottsdale, Arizona
CHARLES F. BOLDEN, JR., TechTrans International, Inc., Houston, Texas
RODNEY A. BROOKS, Massachusetts Institute of Technology Computer Science and Artificial Intelligence Laboratory, Cambridge, Massachusetts
JON H. BRYSON, The Aerospace Corporation (retired), Chantilly, Virginia
BENJAMIN BUCHBINDER, Consultant, Bonaire, Antilles
BERT BULKIN, Lockheed Missiles and Space (retired), Woodbridge, California
ROBERT F. DUNN, U.S. Navy (retired); National Consortium for Aviation Mobility, Alexandria, Virginia
SANDRA M. FABER, University of California Observatories/Lick Observatory, University of California, Santa Cruz
RICCARDO GIACCONI, Johns Hopkins University and Associated Universities, Inc., Washington, D.C.
GREGORY HARBAUGH, Sun N Fun Air Museum, Lakeland, Florida
TOMMY W. HOLLOWAY, NASA (retired), Houston, Texas
JOHN M. KLINEBERG, Space Systems/Loral (retired), Redwood City, California
VIJAY KUMAR, University of Pennsylvania, Philadelphia, Pennsylvania
LT GEN FORREST S. McCARTNEY, U.S. Air Force (retired), Indian Harbour Beach, Florida
STEPHEN M. ROCK, Stanford University, Stanford, California
JOSEPH ROTHENBERG, Universal Space Network, Darnestown, Maryland
JOSEPH H. TAYLOR, JR., Princeton University, Princeton, New Jersey
ROGER E. TETRAULT, McDermott International, Inc. (retired), Punta Gorda, Florida
VADM RICHARD H. TRULY, U.S. Navy (retired); National Renewable Energy Laboratory, Golden, Colorado

Enclosure B

Project Overview

Background

The Hubble Space Telescope was originally launched aboard the space shuttle in 1990, with a designed mission lifetime of 15 years. Since then the telescope has been repaired or upgraded four times, each requiring a very complex, dedicated space shuttle mission and unique HST servicing support equipment. Over its lifetime, HST has been an unprecedented scientific success, having earning extraordinary scientific and public recognition for its contributions to all areas of astronomy. Prior to the accidental loss of the space shuttle Columbia and crew in February 2003 there had been plans for another shuttle servicing mission, designated SM-4, to replace aging spacecraft batteries and gyroscopes and to install two new science instruments on the telescope.

Following the Columbia accident, the Columbia Accident Investigation Board (CAIB) was created to determine the cause of the accident and to advise NASA about steps to prevent future accidents. In its August 2003 report, the CAIB noted the inherent risk in any form of human spaceflight, and it made 29 recommendations, 15 of which were required to be completed before the space shuttle could return to flight. The report made specific recommendations about on-orbit inspections and repairs, and it noted differences between future flights to the International Space Station (ISS), which could be used as a safe haven, and other possible destinations. NASA subsequently formed an internal committee, called the Stafford-Covey Return-to-Flight committee, to provide advice about how to implement the CAIB recommendations and any other related actions. NASA Administrator Sean O'Keefe committed the agency to following all recommendations from both groups.

In mid-January 2004 Mr. O'Keefe announced that, as a consequence of safety considerations, NASA would reduce its shuttle manifest to only the 25 planned missions to the ISS. The decision was also made, on the basis of risk, to not pursue SM-4, but instead to investigate other options to extend the life of HST. Following that announcement Senator Barbara Mikulski asked O'Keefe to seek an independent opinion on whether the decision was, in fact, required to comply with the CAIB recommendations, and O'Keefe asked the CAIB chair, Adm. Harold Gehman, to review the matter. In his March 5, 2003, letter to Mikulski, Gehman said that "the Board is split on the merits of flying this mission." He also indicated that "whether to fly another mission to the Hubble is one of the public policy debates this nation should have," and he called for a "deep and rich study of the entire gain/risk equation (to) answer the question of whether an extension of the life of (HST) is worth the risks involved."

O'Keefe subsequently asked the National Academies for the study.

NASA plans to continue operation of the HST until it can no longer support scientific investigations—currently anticipated to occur in the 2007-2008 time frame. The telescope's life may, in fact, be extended if NASA is successful in employing operational techniques to preserve battery and gyroscope functions. Meanwhile, NASA is investigating innovative ways to extend the science lifetime of the HST for as long as possible, including robotic servicing. Current plans are to safely de-orbit HST by means of a robotic spacecraft by approximately 2013.

Statement of Task

The committee will conduct an independent assessment of options for extending the life of the Hubble Space Telescope. The study will address the following tasks:

1. Assess the viability of a space shuttle servicing mission that will satisfy all recommendations from the CAIB, as well as ones identified by NASA's own Return-to-Flight activities. In making this assessment, compare the risks of a space shuttle servicing mission to HST with the risks of a shuttle mission to the ISS and, where there are differences, describe the extent to which those differences are significant. Estimate to the extent possible the time and resources needed to overcome any unique technical or safety issues associated with HST servicing that are required to meet the CAIB recommendations, as well as those from the Stafford-Covey team.

2. Survey other available engineering options, including both on-orbit robotic intervention and optimization of ground operations, that could extend the HST lifetime.

3. Assess the response of the spacecraft to likely component failures and the resulting impact on servicing feasibility, lost science, and the ability to safely dispose of HST at the end of its service life.

4. Based upon the results of the tasks above, provide a benefit/risk assessment of whether extension of HST service life, via (a) a shuttle serving mission if one is deemed viable under task #1 and/or (b) a robotic servicing mission if one is deemed viable under task #2, is worth the risks involved. The assessment should include consideration of the scientific gains from different options considered and of the scientific value of HST in the larger context of ground and space-based astronomy and science more broadly. Special attention should be paid to the practical implications of the limited time available for meaningful intervention robotically or via the shuttle.

The committee is not expected to make either organizational or budgetary recommendations, but it may need to consider cost as a factor in weighing the relative benefits of alternative approaches.

The committee will investigate the possibility of providing an interim report to NASA that addresses a portion of the items in the task statement in advance of delivering a full final report if such an approach is deemed feasible and able to provide early, credible answers to the questions being considered.

Enclosure C

Acknowledgement of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Roger Blandford, Stanford University,
Wendy Freedman, Observatories of the Carnegie Institution,
Takeo Kanade, Carnegie Mellon University,
George Paulikas, The Aerospace Corporation (retired),
Harvey Tananbaum, Smithsonian Astrophysical Observatory,
Kathryn Thornton, University of Virginia,
Chris Whipple, ENVIRON International Corporation, and
Peter Wilhelm, Naval Research Laboratory.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by William Press, Los Alamos National Laboratory, and John Ahearne, Sigma Xi. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

D
State of the Art in Robotics

Robotics is a field that has many exciting potential applications. It is also a field in which expectations of the public often do not match current realities. Truly incredible capabilities are being sought and demonstrated in research laboratories around the world. However, achieving these capabilities with real robots in real environments faces many hurdles. It is true that robotic systems can be stronger and faster than humans, can go places too dangerous for a human to venture, and can operate without fatigue while performing highly repetitive and precise tasks. However, it is very difficult to build a mechanical device (e.g., a robotic arm) that has dexterity comparable to a human's limbs. It is even more difficult to build a computer system that can perceive its environment, reason about the environment and the task at hand, and control a robotic arm with anything remotely approaching the capabilities of a human being.

Hollywood's depiction of robots often endows them with human-like intelligence and decision-making capabilities, but real robots fall far short of this image. A robot is simply a machine that "synthesizes some aspect of the human function."[1] In general a robot involves some level of *automation*, which is the attribute of being able to perform a task or a sequence of tasks and adapt to a well-defined and predetermined class of variations. A robot may also exhibit *autonomy*, which is the ability to make decisions the way a human being might make decisions. However, the level of autonomy that has been achieved in today's robotic systems is no match for even the simplest decision-making capabilities of a human.

Many robots are teleoperated. In *teleoperation*, a human operator controls the robot directly while monitoring some or all the information that the robot sensors acquire. Teleoperated robots have been used effectively by human operators to augment their skills or to be able to operate in remote, usually hazardous or inaccessible, environments. For example, the manipulators used on the International Space Station (ISS) and the shuttle are teleoperated. Surgical robots that allow surgeons to perform procedures while operating through tiny ports are also teleoperated. The key feature of teleoperation is that it exploits the perceptual capabilities and reasoning power of the human operator rather than relying only on the sensors and computers available to the robot. A key requirement for successful teleoperation is that the communication link between the human operator and the robot is sufficient to provide enough information for the remote operator to make decisions and to issue appropriate control commands in a correct and timely manner. Teleoperated robots typically require and exhibit very little autonomy because of the presence of the human operator in the loop.

It is useful to look at some well-known applications of robotics to understand the difference between automated, autonomous and teleoperated robots.

One of the most visible and successful application of robotics is in factories and on the shop floor. Here, reprogrammable, multi-link robotic arms have replaced special purpose machines to perform precise and quick repetitive operations, such as pick and place tasks, for handling parts and tools and for assembling parts. The advantage of using robots in these applications is that their reconfigurability and flexibility make it possible for one assembly line to be multifunctional and be adapted for a range of parts or products. However, a production facility or a factory is typically a highly structured environment. Precisely manufactured parts arrive on schedule at predetermined positions and orientations for robotic operation, and all operations are, for the most part, predictable. Once a robot is programmed, very little "intelligence" or autonomy is required of the robot for it to perform its limited set of functions. Very little adaptation to uncertainties is required. In spirit, these robots are closer to machines like programmable looms or dishwashers than to Hollywood's R2D2.

[1] J.J. Craig, *Introduction to Robotics*, Addison-Wesley, 1999.

Another recent, very visible application of robotics is the pair of Mars Exploratory Rovers (MERs), Spirit and Opportunity. These very successful mobile robots exhibit multiple levels of autonomous or semi-autonomous operation. These rovers have sensors which provide information about the environment in which they are operating, about their position in that environment, and about the status of the task they are performing. The sensors provide information to computers, that reason about the state of the robot and the environment, and calculate the commands sent to the robot's actuators to control its motion and activities. Some of this reasoning is done onboard the vehicle. However, much of the high-level reasoning and decision-making is done by the remote human users, albeit infrequently because of the time delays associated with communication between the rovers and mission control on Earth. For example, remote human users set the science objectives (e.g., on which rock to place an instrument) and issue high level commands (e.g., "go to that rock"). The rovers then execute these commands using onboard sensors and computers to determine and follow safe paths through the terrain. Importantly, the onboard autonomy is limited primarily to the specific tasks of navigation and instrumentation placement. The rovers have some limited ability to adapt to operating conditions and the environment. When unexpected situations or failures are encountered, the rovers can stop and wait for the remote human users to issue a new set of commands. Human users can also make the decision to send new software to the rovers or patch software bugs that may be discovered during the mission. Thus, while these robots are not, strictly speaking, teleoperated, there is an element of teleoperation in the functioning of these rovers. At the same time, the rovers exhibit a significantly greater degree of autonomy than the automated factory robots discussed earlier. This combination of autonomy with an element of teleoperation is often called *supervised autonomy.*

There are many remotely operated vehicles like Spirit and Opportunity that have been deployed on Earth. Rovers have been used for nuclear reactor inspection at Three Mile Island and have been deployed by the military for de-mining in Bosnia and for reconnaissance in caves in Afghanistan. In Iraq teleoperated rovers with manipulators are used for disruption and disposal of improvised explosive devices. Robotic submersibles have been used in the deep sea for exploration tasks by the marine science community, for inspection and maintenance tasks by the oil industry, and for salvage of wrecks like the Titanic. The level of autonomy employed in these devices varies. It is not feasible to teleoperate the MERs because of the time delays associated with communications, hence supervised autonomy is used. It is feasible, however, to teleoperate a vehicle driving over a minefield. Thus a military robot driving clearing mines through a minefield may not require the level of autonomy that the MERs require.

Robots can also be seen in the service industry. There are commercial products for vacuum cleaning, for mowing lawns, and for assisting people with disabilities. Humanoid robots are being developed for entertainment. There are many sophisticated toys that employ robotics technology. Amusement parks use programmable, articulated mechanical devices to mimic biological motion. While many of these applications provide successful examples of autonomous operation, there are no examples of dexterous manipulation.

Deciding what tasks can or should be performed autonomously by a robotic system depends heavily on the details of the specific mission. Further, enabling those autonomous operations requires an extensive, dedicated research and development program, which begins in the laboratory and culminates in field demonstrations before actual deployment on a mission. For the MER rovers, autonomous navigation was identified as having significant mission benefits and was achieved only after years of focused research and development, such as identifying obstacles using computer vision and relative state estimation using wheel, inertial and optical sensors. Manipulation with robotic arms is a very different type of task and requires a similar, focused development activity if it is to be automated at any level. Robotic arms have been used extensively on the shuttle and on the ISS to perform assembly-class operations, but up to now all of these operations have been done in a teleoperated mode with no autonomy.[2] Significant training of the astronauts is required to qualify them to use these robotic arms.

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[2] Astronauts at the site monitor and control the motions of the arms directly. The information they use includes direct visual observations plus views from video cameras and readings from joint angle sensors mounted on the

Automated rendezvous, capture and grappling of HST and robotic servicing with dexterous manipulators cannot be performed via direct teleoperation because of the time delays in the communication link between the orbiting robot and the ground station.[3] Supervised autonomy is the appropriate mode of operation for the robotic servicing mission. It allows shared control where the on-board computers can control the motion of the arms and effectors based on sensory information while human operators on the ground can make mission-critical decisions. However, the successful implementation of supervised autonomy requires that the manipulators, sensors and control software be sufficiently sophisticated to perform assembly and disassembly tasks in an environment that is not well structured, unlike the structured environment of the factory and the shop floor, for example.

It is also important to note that although supervised autonomy has been extensively studied in research laboratories, its robustness and reliability for a mission as complex as the HST servicing has not yet been verified. There are very few examples of field-tested space operations involving manipulation or assembly with autonomy or supervised autonomy. In 1970, rendezvous and capture with a non-cooperative target was performed by the Soviets with a human operator in control and without any communication time delays. In 1998, collaboration between ESA and NASDA produced a moderately successful demonstration on the Japanese Engineering Test Satellite (ETS) VII. This involved manipulation of a 2-meter long, six degree-of-freedom manipulator arm attached to a 2500 kg satellite with the coordinated control of the manipulator and the base. The ETS VII mission demonstrated autonomous rendezvous and capture of a target satellite. However, in this demonstration, the target was specially designed for capture, with appropriate fiduciaries for relative orientation, positioning and capture. Thus the proposed HST robotic servicing mission will require the development, testing and validation of new software and hardware, which would advance the state-of-the-art of robotics technology.

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arms. They control the motion of the arms using a joystick to issue commands that control the torque produced by the motors embedded in the arm.

[3] The delay expected between the ground and HST is approximately 2.5 seconds. In order for teleoperation to work successfully, the information supplied to the user must be sufficient and timely. When controlling a dynamic system, excessive delays in the information transfer between the device and the user can cause the system to go unstable. In particular, the time delay must be small enough so that it remains a small fraction of the dominant time constants that characterize the dynamics of the system being controlled. If only the position of the robotic arm is being controlled, a reasonable performance can be achieved by limiting the speed of robot motions during teleoperation. However, if force feedback is used, even delays of a fraction of a second are known to cause instabilities during teleoperation and pose difficulties for a human operator. Force feedback is needed for inserting instruments into the HST, and for mating and de-mating of connectors.

E
Acronyms

2MASS	Two Micron All Sky Survey
ACS	Advanced Camera for Surveys
ALMA	Atacama Large Millimeter Array
AO	adaptive optics
ASCS	Aft Shroud Cooling System
C&DH	command and data handling
CAD	computer assisted design
CAIB	Columbia Accident Investigation Board
CCD	charge coupled device
COS	Cosmic Origins Spectrograph
COSTAR	Corrective Optics Space Telescope Axial Replacement
CSCS	Contingency Shuttle Crew Support
DARPA	Defense Advanced Research Projects Agency
DBA	diode box assembly
DIU	data interface unit
DM	de-orbit module
DMU	data management unit
DR	dexterous robot
DSC	data management unit (DMU) to scientific instrument (SI) command and data handling (C&DH) Cross-Strap
ECU	electronic control unit
EDO	Extended Duration Orbiter
EM	ejection module
ESA	European Space Agency
ESM	Electronic Support Module
ESTR	Engineering Science Tape Recorder
ET	external tank
ETS	Engineering Test Satellite
EVA	extravehicular activity
FGS	fine guidance sensor
FOC	Faint Object Camera
FOS	Faint Object Spectrograph
FUSE	Far-Ultraviolet Spectrographic Explorer
GA	grapple arm
GALEX	Galaxy Evolution Explorer
GHRS	Goddard High Resolution Spectrograph
GN&C	guidance, navigation, and control
GSFC	Goddard Space Flight Center
HRSDM	Hubble Robotic Servicing and Disposal Mission
HRV	Hubble Rescue Vehicle
HST	Hubble Space Telescope

INTELSAT	International Telecommunications Satellite
IR	infrared
ISS	International Space Station
JDEM	Joint Dark Energy Mission
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
JWST	James Webb Space Telescope
KSC	Kennedy Space Center
LED	Light-emitting diode
LF	logistics flight
LMSC	Lockheed Missiles and Space Company
MER	Mars Exploratory Rover
MLI	multi-layer insulation
MMOD	Micro-Meteoroid Orbital Debris
MSFC	Marshall Space Flight Center
MSS	Magnetic Sensing System
MTBF	mean time before failure
MTTF	mean time to failure
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NCC	NICMOS Cryocooler
NCS	NICMOS cooling system
NIC	Near-Infrared Camera
NIC3	lowest-resolution mode of NICMOS
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NOBL	New Outer Blanket Layer
NRC	National Research Council
OBSS	Orbiter Boom Sensor System
OCE-EK	Optical Control Electronics Enhancement Kit
OCEK	Optical Control Electronics Enhancement Kit
OTA	Optical Telescope Assembly
OV	orbiter vehicle
PCU	power control unit
PDR	preliminary design review
PRA	probabilistic risk assessment
PRT	power ratchet tool
RCC	reinforced carbon-carbon
RFI	radio frequency interference
RM	robotic module
RMS	remote manipulator system
RSU	rate sensor unit
RSU	rate sensor units

RTF	return to flight
RWA	reaction wheel assembly
SA3	solar array 3
SADE	solar array drive electronics
SI	scientific instrument
SM	servicing mission
SMM	Solar Maximum Mission
SNAP	Super Nova Acceleration Probe
SOC	state of charge
SPATEL	Space Telescope reliability Model
SPDM	Special Purpose Dexterous Manipulator System
SRMS	shuttle remote manipulator system
SSAT	S-Band single-axis transmitter
SSR	Solid State Recorder
STIS	Space Telescope Imaging Spectrograph
STS	Space Transportation System
STScI	Space Telescope Science Institute
SYNCOM	geosynchronous communications satellite
TID	total ionizing dose
TPS	thermal protection system
TRL	technology readiness level
ULF	utilization and logistics flight
USAF	U.S. Air Force
UV	ultraviolet
UVis	ultraviolet-visible
VIK	voltage improvement kit
VLT	Very Large Telescope (of the European Southern Observatory)
WESTAR	Communications satellite originally built by Western Union
WFC3	Wide-field Camera 3
WFPC	Wide Field Planetary Camera
XSS-11	Experimental satellite system (for USAF)

F
Glossary

adaptive optics	a process in which distortions (like those from the Earth's atmosphere) are removed from a telescope's image in real time. First, a wavefront sensor uses a reference star to measure the distortions that are occurring, and the distortions are then removed with a phase corrector.
avionics	the onboard electronics used for operating a space craft, including communications, navigation, and electronic flight management systems
angular resolution	the ability of an instrument, such as a telescope, to distinguish objects that are very close to each other. The angular resolution of an instrument is the smallest angular separation at which the instrument can observe two neighboring objects as two separate objects.
black hole	a region of space containing a huge amount of mass compacted into an extremely small volume. A black hole's gravitational influence is so strong that nothing, not even light, can escape its grasp.
Cepheid variable star	A type of pulsating star whose light and energy output vary noticeably over a set period of time. The time period over which the star varies is directly related to its light output or luminosity, making these stars useful standard candles for measuring intergalactic distances.
dark energy	the residual energy in empty space which is causing the expansion of the universe to accelerate.
de-scope	the reduction or elimination of some objectives, performance requirements, or capabilities compared to those in an earlier baseline plan
end effector	a device or tool connected to the end of a robot arm
fine guidance sensor	the targeting devices aboard HST that lock onto "guide stars" and measure their positions relative to the object being viewed. Adjustments based on these precise readings keep Hubble pointed in the right direction.
flux	the amount of something (such as radiation) passing through a surface per unit time.
gyroscope	a spinning wheel mounted on a non-stationary frame that stabilizes and points a space-based observatory. This spinning wheel resists applied external forces and tends to retain its original orientation in space.
Hubble constant	a number that expresses the rate at which the universe expands with time. Ho appears to be between 60 and 75 kilometers per second per million parsecs. (One parsec is equal to 3.26 light-years and 3.085678 × 1013 kilometers, or approximately 18 trillion miles.)
Milky Way Galaxy	The Milky Way, a spiral galaxy, is the home of Earth, the Sun, and the rest of our solar system.
orbital debris	any man-made object, or portions thereof, in orbit about the Earth which no longer serves a useful purpose
planetary nebula	an expanding shell of glowing gas expelled by a star late in its life.
proto-solar system	matter that is beginning to come together to form a star and its collection of orbiting planets
quasar	the brightest type of active galactic nucleus, believed to be powered by a supermassive black hole. The word "quasar" is derived from quasi-stellar radio source, because this type of object was first identified as a kind of radio source.
ranging device	an instrument or instrument system for measuring the distance, for example between two space craft as they approach one another
reaction wheel	One of four spinning wheels that work by rotating a large flywheel up to 3000 rpm or braking it to exchange momentum with the spacecraft which will make HST turn. The flywheels work together to make the observatory rotate either more rapidly or less

	rapidly toward a new target.
red shift	an apparent shift toward longer wavelengths of spectral lines in the radiation emitted by an object caused by motion of the emitting object away from the observer
spherical aberration	an optical aberration in which light from different parts of a mirror or lens is brought to different foci.
supernova	the explosive death of a massive star whose energy output causes its expanding gases to glow brightly for weeks or months.
teleoperation	the control of robots from a distance
Weibull distribution	a general-purpose reliability distribution used to model material strength and times-to-failure of electronic and mechanical components, equipment, or systems.

G
Biographical Information for Committee Members and Staff

COMMITTEE MEMBERS

LOUIS J. LANZEROTTI (chair) currently consults for Bell Laboratories, Lucent Technologies and is a distinguished professor for solar- terrestrial research at the New Jersey Institute of Technology. Dr. Lanzerotti's principal research interests have included space plasmas, geophysics, and engineering problems related to the impact of space processes on space and terrestrial technologies. He was chair (1984-1988) of NASA's Space and Earth Science Advisory Committee and a member of the 1990 Advisory Committee on the Future of the U.S. Space Program. He has also served as chair (1988-1994) of the Space Studies Board and as a member (1991-1993) of the Vice President's Space Policy Advisory Board. He has served on numerous NASA, National Science Foundation, and university advisory bodies concerned with space and geophysics research. He is a member of the International Academy of Astronautics and is a fellow of the Institute of Electrical and Electronics Engineers, the American Geophysical Union, the American Institute of Aeronautics and Astronautics, the American Physical Society, and the American Association for the Advancement of Science. He is a member of the National Academy of Engineering and has an extensive history of NRC service.

STEVEN J. BATTEL, a private consultant, was an engineer, researcher and manager at the University of Michigan, Lockheed Palo Alto Research Laboratory, University of California (UC), Berkeley, and the University of Arizona Lunar and Planetary Laboratory prior to becoming President of Battel Engineering. At UC Berkeley, Mr. Battel was Project Manager for the Extreme Ultraviolet Explorer (EUVE) Project. Since 1990 his company, Battel Engineering, has provided engineering, development and review services to NASA, DOD, University, and Industrial clients. Areas of specialization include program management, systems engineering, advanced technology, UV optics, RF communications, spacecraft avionics, power systems, high voltage systems, precision electronics and scientific instrument design. Mr. Battel was a member of the HST External Readiness Review Team for SM-2, SM3A and SM3B, the AXAF/Chandra Independent Assessment Team, the TDRS-H/I/J Independent Review Team and the Mars Polar Lander Failure Review Board. He is also a member of the NSO Solar Observatory Council (SOC).

CHARLES F. BOLDEN, JR., a retired U.S. Marine Corps (USMC) major general, is a senior vice president at TechTrans International, Inc. Selected as an astronaut candidate by NASA in 1980, Mr. Bolden qualified as a space shuttle pilot astronaut in 1981 and subsequently flew four missions in space. As pilot of the Space Shuttle Discovery in 1990, Mr. Bolden and crew successfully deployed the Hubble Space Telescope. On his third mission in 1992, he commanded the Space Shuttle Atlantis on the first Space Laboratory (SPACELAB) mission dedicated to NASA's "Mission to Planet Earth." Immediately following this mission, Mr. Bolden was appointed Assistant Deputy Administrator for the NASA. He held this post until assigned as commander of STS-60, the 1994, the first joint U.S./Russian Space Shuttle mission. Upon completion of this fourth mission, Major General Bolden left the space program and returned to operational assignment in the USMC as the Deputy Commandant of Midshipmen at the Naval Academy. He served in a number of Marine Corps and joint service assignments before retiring from the Marine Corps as the Commanding General of the Third Marine Aircraft Wing, MCAS Miramar, San Diego, California, having served more than 34 years. Bolden served on the NRC Committee on the Navy's Needs in Space for Providing Future Capabilities (2003-2004).

RODNEY A. BROOKS is director of the Computer Science and Artificial Intelligence Laboratory at the Massachusetts Institute of Technology, and is the Fujitsu Professor of Computer Science. He is also chief technical officer of iRobot Corp His research is concerned with both the engineering of intelligent robots to operate in unstructured environments, and with understanding human intelligence through building humanoid robots, Dr. Brooks is a Founding Fellow of the American Association for Artificial Intelligence (AAAI) and a Fellow of the American Association for the Advancement of Science (AAAS). He won the Computers and Thought Award at the 1991 International Joint Conference on Artificial Intelligence. He was co-founding editor of the International Journal of Computer Vision and is a member of the editorial boards of various journals including Adaptive Behavior, Artificial Life, Applied Artificial Intelligence, Autonomous Robots and New Generation Computing. He is an elected member of the National Academy of Engineering.

JON H. BRYSON is senior vice president at Aerospace Corporation with executive and supervisory responsibilities for a team supporting space systems. He has served as deputy director of the Air Force component of the National Reconnaissance Office with management responsibilities for unit acquiring and operating several, major space programs. Mr. Bryson served as program manager for two NRO programs that deal with of all aspects of design, development, launch and operation of several, complex spacecraft and their attendant ground stations. He was a program officer for the Office of the Secretary of the Air Force and was responsible for developing the Secretary's policies and budget submissions for several major space programs. Mr. Bryson has experience in developing and executing plans to maximize on-orbit lifetime of failed and/or aging spacecraft, and he has been directly/indirectly responsible for extended mission life on over a dozen satellites and recovering use of another dozen failed satellites.

BENJAMIN BUCHBINDER has extensive experience in the development and application of risk assessment methods, in the use of quantitative methods to support management decision-making related to safety and programmatic risk, and in the communication of risk assessment results and their significance, to a wide range of audiences. Mr. Buchbinder served as risk assessment program manager for Futron Corporation (1994-1997), with responsibility for business development and project management in probabilistic risk assessment and programmatic risk management. As program manager for risk assessment at NASA Headquarters Office of Safety and Mission Assurance (1987-1994) he led NASA's probabilistic approach to risk assessment for human spaceflight, expendable launch vehicles, range safety, space payloads, and special facilities (wind tunnels and solid rocket processing facilities).

BERT BULKIN is the emeritus director of Scientific Space Programs at Lockheed Missiles and Space Company. Mr. Bulkin served as the Program Manager for the Hubble Space Telescope and was also in charge of its maintenance, refurbishment, logistics, and servicing. Previously, he was the director of Advanced Systems Development at ITT's Electro-Optical division. He has a B.S. in Aeronautical Engineering from the University of California, Los Angeles and completed postgraduate work at the University of California, Los Angeles and the University of Santa Clara. Mr. Bulkin was a member of the External Independent Readiness Review Board for the Chandra Telescope and was a member of the Independent Review Team for the Lyman Spitzer Infra-red Telescope. He served on the NRC Committee on Engineering Challenges to the Long-Term Operation of the International Space Station (1998-2000).

ROBERT F. DUNN is vice admiral, U.S. Navy (retired). Admiral Dunn's naval career experience includes assignments as Deputy Chief of Naval Operations for Air Warfare; Commander of Naval Air Forces, U.S. Atlantic Fleet; Commander of Naval Reserve Forces; Commander of Naval Military Personnel Command; and Commander of Naval Safety Center. He has served as an independent consultant to the aerospace industry, defense non-profit institutions, non-defense government agencies, an environmental services company, corporate boards, the NASA Aerospace Safety Advisory Panel, and the U.S. Naval Institute. He is presently the president of the Naval Historical Foundation and the president of National Consortium for Aviation Mobility, an alliance of Small Aircraft Transportation Laboratories.

SANDRA M. FABER is a professor of astronomy at the UCO/Lick Observatory, University of California, Santa Cruz and University Professor at the University of California. Her research focuses on the formation and evolution of galaxies and the evolution of structure in the universe. She utilizes ground-based optical data obtained with the Lick 3-meter and Keck 10-meter telescopes. She was a member of the Wide-Field Camera (I) Team of HST and has used Hubble Space Telescope observations to study distant galaxies and detect black holes in nearby galaxies. Dr. Faber is also a core member of the DEEP (Deep Extragalactic Evolutionary Probe), a large-scale survey of distant, faint field galaxies using the Keck twin telescopes and the Hubble Space Telescope. She is a member of the National Academy of Sciences, and has served as a member of the NRC Astronomy Survey Study (1978-1983), the Committee on Astronomy and Astrophysics (1992-1994), and the Committee on Physics of the Universe (2000-2001).

B. JOHN GARRICK, independent consultant, was a cofounder of PLG, Inc., an international engineering, applied science, and management consulting firm, from which he retired as president and chief executive officer in 1997. His professional interests include risk assessment in nuclear energy, space and defense, chemicals and petroleum, and transportation. A past president of the Society for Risk Analysis, Dr. Garrick is also a fellow of three professional societies and a member of the National Academy of Engineering. He has received numerous awards, including the Society for Risk Analysis Distinguished Achievement Award. Dr. Garrick was appointed to the U.S. Nuclear Regulatory Commission Advisory Committee on Nuclear Waste in 1994 and served for 10 years (1994-2004), four years as chair. On September 10, 2004, President George W. Bush appointed Dr. Garrick to the U.S. Nuclear Waste Technical Review Board with the designation of Chairman. He has served on many National Research Council committees, including several associated with the space program. Dr. Garrick received his B.S. in physics from Brigham Young University and his M.S. and Ph.D. in engineering and applied science from the University of California, Los Angeles; he is also a graduate of the Oak Ridge School of Reactor Technology.

RICCARDO GIACCONI is president of Associated Universities, Inc., and a research professor at Johns Hopkins University. His research is in experimental astrophysics, specifically extragalactic astronomy and the early phases of formation of the universe. Dr. Giacconi is one of three 2002 recipients of the Nobel Prize in Physics, which he received for pioneering contributions to astrophysics, which have led to the discovery of cosmic x-ray sources. In 1973 he was appointed Professor of Astronomy at Harvard University where he led the Einstein Observatory Program. In September of 1981 In September of 1981, Dr. Giacconi was appointed Director of the new Space Telescope Science Institute (STScI). STScI, managed by the Association of Universities for Research in Astronomy (AURA) for NASA, is the center of scientific operations and research for the Hubble Space Telescope (HST). He later moved to Germany to become Director-General of the European Southern Observatory. In 1999, he returned to the United States to become President of Associated Universities, Inc. (AUI), which operates the National Radio Astronomy Observatory. Dr. Giacconi is an elected member of the National Academy of Sciences, and he has served on the NRC Space Studies Board (1981-1984 and 1989-1993), the Astronomy and Astrophysics Task Group (1984-1988), and the Panel on High Energy Astronomy (1979-1983).

GREGORY J. HARBAUGH is currently vice president of Sun ‘n Fun Fly In, Inc., and director of the Florida Air Museum. Mr. Harbaugh joined the staff at Johnson Space Center after graduation from Purdue in 1978. While at NASA, he held engineering and technical management positions in Space Shuttle flight operations. Mr. Harbaugh became an astronaut in August 1988. His technical assignments included work in the Shuttle Avionics Integration Laboratory (SAIL), the Shuttle Remote Manipulator System (RMS), telerobotics systems development for Space Station, the Hubble Space Telescope servicing mission development, spacecraft communicator (CAPCOM) in Mission Control, and extravehicular activity (EVA) for the International Space Station (ISS). He was assigned as the backup EVA crew member and capsule communicator (Capcom) for STS-61, the first Hubble Space Telescope servicing mission. He flew four space shuttle missions, (STS 39, 54, 71, 82) including first shuttle - MIR docking (STS 71) and 2nd HST servicing mission (STS 82). Performed 3 spacewalks, (2 on HST), for total EVA time of eighteen hours and twenty-nine minutes. From 1997-2001 Mr. Harbaugh served as Manager of the Extravehicular Activity Project Office, with program management responsibility for all aspects of NASA's spacewalk industry, including spacesuits, tools, training, tasks and operations for the Space Shuttle, the International Space Station, and future planetary missions. Mr. Harbaugh left NASA in March 2001.

TOMMY HOLLOWAY retired in 2002 as manager of the International Space Station Program Office for NASA's Johnson Space Center. Mr. Holloway was named space station manager in April 1999 after serving as manager of the Space Shuttle program for nearly four years. He began his career with NASA in 1963, planning activities for Gemini and Apollo Flights at what was then known as the Manned Spacecraft Center. He was a flight director in Mission Control for early Space Shuttle flights and became chief of the office in 1985. In 1989, he was named assistant director for the Space Shuttle Program for the Mission Operations Directorate. He served as deputy manager for program integration with the Space Shuttle Program and director of the Phase I Program of Shuttle-Mir dockings before being named Space Shuttle program manager in August 1995.

JOHN M. KLINEBERG recently retired as president of Space Systems/Loral, a major provider of commercial communications satellite systems and services, and vice president of Loral Space & Communications, of which SS/L is a wholly owned subsidiary. Before becoming the president of SS/L in 1999, Dr. Klineberg was executive vice president for Globalstar programs, where he led the successful development, production and deployment in orbit of the Globalstar satellite constellation for providing a new generation of telephony services. Before joining Loral in 1995, Dr. Klineberg spent 25 years with NASA where he was director of the NASA Goddard Space Flight Center; director of the Lewis (now Glenn) Research Center; deputy director of the Lewis Research Center; deputy associate administrator for Aeronautics and Space Technology at NASA Headquarters, and a research scientist at the Ames Research Center. He is a member of the NRC Aeronautics and Space Engineering Board, and chaired the NRC 2003 study of NASA Aeronautics Technology Programs.

VIJAY KUMAR is a professor and deputy dean for research in the School of Engineering & Applied Sciences at University of Pennsylvania. He is the director of the General Robotics, Automation, Sensing and Perception Laboratory (GRASP). Dr. Kumar's research focuses on robotics, dynamics, and control. He is a Fellow of the American Society of Mechanical Engineers and a senior member of the IEEE. He has served on the editorial board of the IEEE Transactions on Robotics and Automation, ASME Journal of Mechanical Design and the Journal of the Franklin Institute. He serves on many robotics conference committees including the Workshop on Cooperative Control, 2003 (Organizer); the 27th ASME Biennial Mechanisms and Robotics Conference, Montreal, 2002 (Conference chair); the International Conference on Robotics and Automation (Program Committee), the International Conference on Intelligent Robots and Systems (Program Committee), and Robotics: Systems and Science (Area Chair). He is the co-founder of Bio Software Systems, a start-up commercializing software for systems biology in Camden, N.J.

FORREST S. MCCARTNEY retired as vice president for Launch Operations at Lockheed Martin Astronautics Cape Canaveral Air Station, Florida and is a retired U.S. Air Force Lt. General. McCartney was the commander of Air Force Space Division in Los Angeles, California (1983-1986) and was previously the Space and Missile Systems Organization at Los Angeles AFS deputy for space communications systems, with practically all the military communications satellite programs under his purview. In 1979, Mr. McCartney transferred to Norton AFB to become the Vice Commander of the Ballistic Missile Office. He became the Commander of the Ballistic Missile Office and Director of the M-X Program in 1980. In 1982, he was appointed Vice Commander of Air Force Systems Command's

Space Division. In the wake of the Challenger accident, Mr. McCartney was appointed Director of the Kennedy Space Center on loan from the Air Force. He retired from the Air Force in August 1987, but continued to serve as the director of the Kennedy Space Center for another four years.

STEPHEN M. ROCK is a professor in the Department of Aeronautics and Astronautics and the director of the Aerospace Robotics Laboratory at Stanford University, Dr. Rock's interests include the development and experimental verification of advanced control techniques for robotic and vehicle systems. Prior to joining the Stanford faculty, Dr. Rock led the Controls and Instrumentation Department of Systems Control Technology, Inc. In his eleven years at SCT he performed and led research in four main areas: integrated control; fault detection, isolation and accommodation; turbine engine modeling and control; and parameter identification. Dr. Rock served on the NRC Panel on Vehicle Applications (1984-1984), the Committee on the Use of the International Space Station for Engineering Research and Technology Development (1995-1996), and the Committee on Engineering Challenges to the Long-Term Operation of the International Space Station (1998-2000).

JOSEPH H. ROTHENBERG is currently president and a member of the board of directors of Universal Space Network. Mr. Rothenberg, who joined NASA in 1983, was named associate administrator for Space Flight January 1998 and was in charge of NASA's human exploration and development of space. Before coming to NASA Headquarters, he served as director of the NASA Goddard Space Flight Center. As associate administrator, Mr. Rothenberg was responsible for establishing policies and direction for the Space Shuttle and International Space Station programs, as well as for space communications and expendable launch services. Rothenberg joined Goddard in 1983 and was responsible for space systems development and operations, and for execution of the scientific research program for the NASA Earth-orbiting science missions. He is widely recognized for leading the development and successful completion of the first servicing mission for the Hubble Space Telescope, which corrected the telescope's flawed optics. From 1981 to 1983, he served as executive vice president of Computer Technology Associates, Inc., Space Systems Division where he managed all ground test and operations systems-engineering projects. Those projects included the Hubble Space Telescope, Solar Maximum repair mission, and space tracking and data system architecture projects.

JOSEPH H. TAYLOR, JR. is the James S. McDonnell Distinguished University Professor of Physics and former dean of the faculty at Princeton University. He is a radio astronomer and physicist who, with Russell A. Hulse, was the co-recipient of the 1993 Nobel Prize for Physics for their joint discovery of the first binary pulsar. He has won several other awards, including the Wolf prize in Physics, The National Academy of Sciences Henry Draper medal, the American Astronomical Society's Dannie Heineman prize, the Magellanic Premium of the American Philosophical Society, and he was the Albert Einstein Society's Einstein Prize Laureate. Taylor is an elected member of the National Academy of Sciences, and he has served as co-chair of the NRC Task Group on Gravity Probe B (1994-1995) and member of the Committee on Space Astronomy and Astrophysics (1981-1982), the Committee on Radio Frequencies (1980-1986). He also served as co-chair of the Astronomy and Astrophysics Survey Committee (1998-2000), and currently serves on the Board on Physics and Astronomy.

ROGER E. TETRAULT is the retired CEO and chairman of the board of McDermott International Corp. McDermott was an S&P 500 corporation engaged in the construction of Electric Power Generation Facilities, the construction of offshore Oil and Gas platforms and the laying of Pipelines. Additionally, it was the sole supplier of Nuclear Reactors to the Navy and was the Prime Contractor at a number of DOE National Facilities. Previously, he was a senior vice president of General Dynamics Corp. (GD). During his tenure with GD, he was president of Electric Boat, the shipyard that manufactured Nuclear Powered Submarines. He was also the president of the Land Systems Division which made Armored Vehicles, including the Abrams Tank. He is a member of the NASA Advisory Council and served as a Board Member on the Columbia Accident Investigation Board.

RICHARD H. TRULY is the director of the National Renewable Energy Laboratory (NREL). Truly began his career as a Naval aviator and retired as a Vice Admiral in 1989. He was among the first military astronauts selected in 1965 to the USAF Manned Orbiting Laboratory program in Los Angeles, California. He became a NASA astronaut in 1969 and was a member of the Astronaut support crew and capsule communicator for all three of the manned Skylab missions (1973) and the Apollo-Soyuz mission (1975). In 1977, he piloted the Shuttle Enterprise during the Approach and Landing Test program. In 1981, Truly served as the pilot of STS-2, which was the first re-flight of the newly designed space shuttle. In 1983, Truly commanded STS-8, the first nighttime Shuttle launch and landing. He has spent over 200 hours in space on two spaceflights. Truly left NASA in 1983 to become the first commander of the Naval Space Command, Dahlgren, Virginia. He returned to NASA and from 1986 to 1989, served as NASA Associate Administrator for Space Flight. From 1989 to 1992, he served as NASA Administrator. He subsequently served as vice president of the Georgia Institute of Technology and as director of the Georgia Tech Research Institute. Truly is an elected member of the National Academy of Engineering and has served on the NRC Naval Studies Board (1992-1994).

STAFF

SANDRA J. GRAHAM received her Ph.D. in inorganic chemistry from Duke University in 1990. Her past research focused primarily on topics in bioinorganic chemistry, such as the exchange mechanisms and reaction chemistry of biological metal complexes and their analogs. From 1990 to 1994 she held the position of senior scientist at the Bionetics Corporation, where she worked in the science branch of the Microgravity Science and Applications Division at NASA headquarters. Since 1994 Dr. Graham has been a senior program officer at the Space Studies Board of the National Research Council, where she has directed numerous studies, primarily in the areas of space life sciences and microgravity sciences.

MAUREEN MELLODY served as a program officer at the National Academies from 2002 to 2004, managing policy studies related to aeronautics and space. Previously, she served as the 2001-2002 American Institute of Physics Congressional science fellow in the office of Congressman Howard L. Berman (D-CA), working on issues related to intellectual property. Dr. Mellody received a B.S. degree in physics from Virginia Tech in 1995, an M.S. in applied physics from the University of Michigan in 1997, a Ph.D. in applied physics from the University of Michigan in 2000. She was a post-doctoral research scientist at the University of Michigan in 2001. Her research specialties include acoustics and auditory signal processing.

CELESTE NAYLOR joined the NRC and the Space Studies Board in June 2002 as a senior project assistant. She works primarily with the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope. In recent years she has worked with the Committee on Microgravity Research and the Task Group on Research on the International Space Station. Ms. Naylor is a member of the Society of Government Meeting Professionals and has over 6 years of experience in event management.

AMANDA SHARP, SSB summer undergraduate intern, is a rising senior at Harvard University in Cambridge, Massachusetts. She is currently pursuing a bachelor's degree in physics, but her courses have included significant work in astronomy and math. Her undergraduate research work has included modeling the atmospheric profiles of extrasolar giant planets and laser ablation inductively coupled plasma mass spectrometry.

CATHERINE A. GRUBER is an assistant editor with the Space Studies Board (SSB). She joined SSB as a senior program assistant in 1995. Ms. Gruber first came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board, then as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was also a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a bachelor of arts in natural science from St. Mary's College of Maryland.